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Research article

Production and postharvest quality of *Passiflora edulis* Sims under brackish water and potassium doses

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Abstract: The aim of this research was to assess the yield and postharvest characteristics of 'BRS Sol do Cerrado' sour passion fruits based on irrigation with varying levels of saline water and potassium fertilization. The study was conducted under field conditions at an experimental farm in São Domingos, Paraíba, Brazil. A randomized block design was implemented in a 5 × 4 factorial arrangement, with five levels of electrical conductivity of water (ECw): 0.3, 1.1, 1.9, 2.7, and 3.5 dS m^{-1}, and four potassium doses (KD): 60, 80, 100, and 120% of the recommended amount, with 3 replications. The potassium dose equivalent to 120% of the recommended dose in combination with low-salinity water resulted in the highest fresh mass accumulation in the sour passion fruit. Water electrical conductivity up to 2.7 dS m^{-1}, along with the lowest recommended KD, led to increased levels of soluble solids and ascorbic acid in the sour passion fruit. Irrigation with water of 3.5 dS m^{-1} and using 80 to 100% of the recommended KD enhanced the total sugar content in the sour passion fruit. On the other hand, irrigation with water of 3.5 dS m^{-1} combined with 60% of the recommended KD resulted in a higher pulp yield in the ‘BRS Sol do Cerrado’ sour passion fruit 160 days post-transplantation. Adjustments in potassium fertilization management at different irrigation water salinity levels played a crucial role in maintaining both the production and quality of the sour passion fruit.

Keywords: sour passion fruit; abiotic stress; osmoregulation; plant nutrition

1. Introduction

The Passiflora genus consists of over 500 species of passion fruit, which are distributed in tropical and subtropical areas worldwide, with *Passiflora edulis* Sims being the most prevalent [1,2]. Among these species, *Passiflora edulis* Sims, also known as sour passion fruit, is the most widely grown commercially [3] due to its nutrient-rich fruit and the presence of various biologically active compounds that have immunological and disease-preventive properties [4].

In 2022, the passion fruit production in Brazil exceeded 697 thousand tons, with an average yield of 15,303 kg ha^{-1}. The Northeast region accounted for nearly 70% of the total national production [5]. However, analyzing the historical data from 2013 to 2022, it becomes evident that this region has consistently recorded lower average yields compared to the national average and other regions like the South, Southeast, and Midwest, despite its significant contribution to the annual production.

One potential reason for this situation may be the utilization of water containing elevated salt levels, a prevalent approach adopted by producers in this area due to the water scarcity caused by climatic conditions. The presence of salts in irrigation water reduces the osmotic potential of the soil, thereby limiting the availability of water and nutrients to plants. Additionally, it leads to the accumulation of sodium (Na^+) and chloride (Cl^-) ions to harmful levels [6], which adversely affects the transportation of water within the plant by increasing the hydraulic resistance of the xylem in the root, stem, and leaves [7,8].

Under the condition of salt stress, various crucial processes for plant growth and development, including photosynthesis, lipid and hormonal metabolism, protein synthesis, and enzymatic activity [9], are impacted. As a result, the production and postharvest quality [10,11] are reduced, and in severe cases, cell death occurs due to the generation of reactive oxygen species (ROS) [12].

In this particular scenario, it becomes imperative to employ management strategies that aim to mitigate the detrimental effects of salt stress on crops. One such strategy involves the fertilization with potassium, which directly influences photosynthetic activity, water retention in plant tissues, protein synthesis, and the formation, transportation, and storage of carbohydrates in the phloem [13,14].

Potassium has the ability to alleviate the negative impacts of salt stress through various mechanisms, including reducing the intercellular content of ROS, enhancing the activity of antioxidant enzymes, and promoting nitrogen uptake in plants [15]. Additionally, the provision of K can decrease the uptake of Na and Cl by plants, as these nutrients compete for absorption sites, which can reduce the effects of salt stress. The impact of K on the metabolic processes mentioned above significantly influences the pre- and post-harvest quality of fruits, affecting their morphological, biochemical, and nutritional characteristics, as well as aspects related to their commercialization and industrialization [16].

This research raises the hypothesis that K fertilization plays a role in regulating the metabolic activity of plants, thereby reducing the impact of salt stress on the production, physical, and chemical attributes of sour passion fruit. The aim of this study was to assess the production and postharvest quality of the 'BRS Sol do Cerrado' passion fruit cultivar, irrigated with brackish water and K fertilization in field conditions in the Brazilian semi-arid region.

2. Materials and methods

2.1. Location of the experimental site

The study was conducted from November 2021 to July 2022 in the fruit cultivation sector at the 'Rolando Enrique Rivas Castellón' Experimental Farm, which is part of the Center of Sciences and Agrifood Technology of the Federal University of Campina Grande situated in the municipality of São Domingos, PB, Brazil. The coordinates of the farm are 06º48'50" S latitude and 37º56'31" W longitude, at an elevation of 190 m.

2.2. Experimental design and treatments

A randomized block design was implemented in a 5 × 4 factorial arrangement. Treatments consisted of combination of five levels of electrical conductivity of irrigation water (ECw): 0.3, 1.1, 1.9, 2.7, and 3.5 dS m^{-1}, and four potassium doses (KD): 60, 80, 100, and 120% of the recommended amount, with 3 replications, resulting in a total of 60 experimental plots. The ECw levels were based on a previous study [17]. The 100% dose of potassium corresponded to 345 g of K_2O per plant annually, as per [18], and applications started 20 days after transplanting (DAT). The sour passion fruit genotype used was 'BRS Sol do Cerrado' (BRS SC1), chosen for its demonstrated tolerance to salinity [19]. Seedlings were produced in a controlled ambient on benches. Polyethylene bags measuring 15 × 20 cm were utilized as containers, filled with a substrate (mixture of soil and well-decomposed cattle manure in a 2:1 ratio on volume basis, respectively).

2.3. Experimental set up and condutction

The experimental setup and implementation involved planting three seeds per bag at a depth of 0.5 cm. Once the seedlings emerged, thinning was conducted to retain only one plant per bag. Throughout the seedling production phase, irrigation was carried out using water with an ECw of 0.3 dS m^{-1}. The study was conducted under field conditions using recepients adopted as drainage lysimeters, each with a capacity of 100 L. These recepients were filled with approximately 110 kg of Entisol with a loamy sand texture collected from a nearby private farm. The physical-hydraulic, and chemical properties were analyzed according to the methodologies recommended by [20], obtaining the following values: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and $Al^{3+} + H^{+}$ = 3.00, 2.44, 0.05, 0.12, and 0.69 $cmol_c$ kg^{-1}, respectively; pH (soil:water, 1:2.5) = 6.01; ECse = 0.71 dS m^{-1}; organic matter = 0.21 dag kg^{-1}; sand, silt, and clay = 75.65, 20.21, and 4.34 dag kg^{-1}, respectively; P = 0.53 mg kg^{-1}; SARse = 0.61 $(mmol\ L^{-1})^{0.5}$; ESP = 0.8%; and CEC = 6.25 $cmol_c$ kg^{-1}.

Plants were supported by a vertical trellis system constructed with galvanized steel wire (no. 12) at a height of 1.2 m from the soil surface in the recepient. Nylon twine was used to stake the plants, and once they grew beyond 10 cm above the trellis, the apical bud was pruned to promote the development of two secondary branches, each extending to a length of 1.50 m in opposite directions. After reaching the specified length, the apical buds were pruned again to obtain tertiary branches, which were allowed to grow downwords until they reached 30 cm from the soil surface to prevent potential contamination. Plant spacing was set at 3.0 m between plants and 2.5 m between rows.

Seedlings were transplanted into the recepients 60 days after sowing, coinciding with the emergence of tendrils. For the initial 30 days post-transplantation, all plants received irrigation with an ECw of 0.3 dS m^{-1}; starting from day 31, irrigation was performed using the respective electrical conductivity water.

Urea (45% N), single superphosphate (20% P_2O_5), and potassium sulfate (51.5% K_2O) were utilized for fertilization to provide nitrogen, phosphorus, and potassium, respectively. The nitrogen and potassium fertilization was divided and applied monthly during the crop cycle, maintaining an N/K ratio of 1/1 during flowering, 1/2 at the start of harvest, and 1/3 until the end of harvest. Phosphorus was applied as a single basal dose and mixed into the soil as the recepients were filled, following the guidelines of [18].

Micronutrients were applied every two weeks using Dripsol® micro (Mg = 1.1%; B = 0.85%; Cu (Cu-EDTA) = 0.5%; Fe (FeEDTA) = 3.4%; Mn (Mn-EDTA) = 3.2%; Mo = 0.05%; Zn = 4.2%; with 70% EDTA chelating agent) at a concentration of 1 g L^{-1} through foliar spraying. The Haiten® adhesive spreader was used at a concentration of 0.15 mL L^{-1} during micronutrient applications.

The irrigation water utilized in the treatment with the lowest salinity level (ECw=0.3 dS m^{-1}) originated from a well situated in the experimental area of the CCTA/UFCG. The analysis of this water showed the following characteristics: Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, HCO_3^-, CO_3^{2-}, and Cl^- = 0.17, 0.61, 1.41, 0.29, 0.18, 0.81, and 1.26 $mmol_c$ L^{-1}, respectively. The water had an electrical conductivity (EC) of 0.30 dS m^{-1}, pH of 7.10, and sodium adsorption ratio (SAR) of 2.25 (mmol $L^{-1})^{0.5}$. To obtain waters with varying electrical conductivity levels, sodium chloride (NaCl) was added to the well water and adjusted to the desired electrical conductivities, taking into consideration the relationship between EC and salt concentration [21].

A drip irrigation system was employed, with each plant receiving two pressure-compensating drippers having a flow rate of 10 L h^{-1}. Irrigation was conducted daily starting at 7:00 a.m., with the volume determined by the water balance applied to each recepient. A leaching fraction of 0.2 was applied every 15 days to prevent the excessive accumulation of salts in the root zone.

Weed control was performed by manually removing weeds between the rows of the lysimeters and around the base of the plants. Pests and diseases were prevently controlled using Ridomil Gold®, a fungicide containing Metalaxyl-M (40 g kg^{-1}) and Mancozeb (640 g kg^{-1}), at a concentration of 2.5 g L^{-1}. In addition, the insecticides were also used [Cyptrin 250 CE® (Cypermethrin 250 g L^{-1}) at a concentration of 1 mL L^{-1} and Connect® (Beta-cyfluthrin 12.5 g L^{-1}) and Imidacloprid (100 g L^{-1}) at a dose equivalent to 750 mL ha^{-1} of the commercial product].

2.4. Traits analyzed

The effects of the different treatments were evaluated on the production components and postharvest quality of the sour passion fruits at harvest (160 DAT).

The number of fruits per plant (NFP) was determined by direct counting, and the fresh fruit mass (FFM) was obtained using an analog scale. Additionally, the following physical characteristics of the fruits were assessed: equatorial (ED) and polar (PD) diameter, which were measured with a digital caliper; pulp mass (PM), which was obtained using an analog scale; pulp volume (PV), which was determined with a graduated flask; and pulp yield (PY), which was calculated by dividing PM by FFM. Fruits that had a fully yellow or reddish peel color and naturally detached from the plant were considered to be at the optimal maturity stage.

Following the harvest, the pulp was manually extracted and promptly stored in a freezer at −10 °C. The storage was done using hermetically sealed glass jars as containers. Furthermore, the passion fruit pulp underwent analysis for various postharvest quality traits. These traits included hydrogen potential (pH), soluble solids (SS), ascorbic acid (AA), titratable acidity (TA), total sugars (TS), and the ratio of soluble solids to titratable acidity (SS/TA).

To determine the soluble solids content, a portable digital refractometer (Atago® PAL-1) was utilized. The titratable acidity was measured through titration with 0.1 N NaOH, following the method described by [22]. The ratio of soluble solids to titratable acidity was obtained by dividing the soluble solids content by the titratable acidity content. The hydrogen potential was determined using a pH meter 9 (pH-1900), after its calibration performed using buffer solutions at pH 4.0 and 7.0, as outlined in the methodology proposed by reference [23]. The total sugars were determined using the anthrone method, as described in the methodology provided by [24]. Lastly, the ascorbic acid contents were determined through titration with a 2,6-dichlocrophenolindophenol (DCPIP) solution, following the methodology proposed by reference [25].

2.5. Stastistical analysis

The results were assessed through a principal component analysis (PCA) to examine the multivariate structure, condensing the information from the original dataset into fewer dimensions. The linear combinations of the original variables, derived from eigenvalues ($\lambda \geq 1.0$) in the correlation matrix, explained over 10% of the total variance [26]. Following dimension reduction, a multivariate analysis of variance was conducted on the variables of each component using the test recommended by [27] at a probability level of 0.05 for irrigation water electrical conductivity, potassium doses, and their interaction. Only variables with a correlation coefficient of 0.65 or higher were retained in each principal component (PC) [28].

Statistical analyses were carried out using Statistica v. 7.0 software [29]. The data underwent the Shapiro-Wilk normality test, and upon confirmation of normality, an analysis of variance was performed using the F test ($p \leq 0.05$). In cases of significance, linear and quadratic polynomial regression analyses were conducted for the factors under study with the statistical software SISVAR-ESAL [30].

3. Results and discussion

3.1. Principal component analysis (PCA) and multivariate variance

The original variables' multidimensional space underwent reduction to two principal components (PC1 and PC2) with eigenvalues exceeding $\lambda \geq 1.0$, as indicated by [31]. The eigenvalues and the percentage of explained variance for each component (Table 1) collectively accounted for 64.75% of the total variation. PC1 elucidated 40.45% of the total variance, encompassing the majority of variables, while PC2 explained 24.30% of the residual variance.

There was a notable impact ($p \leq 0.01$) of the interaction between the electrical conductivity levels of water (ECw) and the KDs for PC1 and PC2 (Table 1). Upon separate examination, a significant effect ($p \leq 0.01$) was noted for the ECw levels in both principal components and for the KDs in PC1. In PC2, the KDs showed a significant effect ($p \leq 0.05$).

The mean values for the number of fruits per plant, the polar and equatorial diameter, the fresh fruit mass, the pulp mass, the pulp volume, the hydrogen potential, the soluble solids, and ascorbic acid are detailed in Table 2.

Table 1. Eigenvalues, percentage of total variance explained in the multivariate analysis of variance, probability of significance by Hotelling's test (*p*-value) for the factors electrical conductivity of irrigation water (ECw), potassium doses (KD), and ECw × KD interaction, and coefficients of correlation (r) between original variables and principal components.

	Principal Components (PCs)	
	PC1	PC2
Eigenvalues (λ)	3.64	2.18
Percentage of total variance (S^2%)	40.45	24.30
Hotelling test (T^2) for electrical conductivity of water (ECw)	0.01	0.01
Hotelling test (T^2) for potassium doses (KD)	0.01	0.05
Hotelling test (T^2) for interaction (ECw × KD)	0.01	0.01

PCs	Coefficient of correlation								
	NFP	PD	ED	FFM	PM	PV	pH	SS	AA
PC1	−0.15	0.66	0.87	0.91	0.85	0.89	0.05	−0.05	0.11
PC2	−0.79	0.06	0.15	−0.12	−0.06	−0.05	0.74	0.73	−0.65

ECw-Electrical conductivity of water, KD-potassium dose; NFP-number of fruits per plant, PD-polar diameter; ED-equatorial diameter; FFM-fresh fruit mass; PM-pulp mass; PV-pulp volume; pH-hydrogen potential; SS-soluble solids; AA-ascorbic acid.

Table 2. Mean values of number of fruits per plant, polar diameter, equatorial diameter, fresh fruit mass, pulp mass, pulp volume, hydrogen potential, soluble solids, and ascorbic acid of sour passion fruit plants, irrigated with saline water and subjected to potassium fertilizer.

TREAT	Mean values								
	NFP	PD	ED	FFM	PM	PV	pH	SS	AA
EC1KD1	13.33 ± 3.18	82.56 ± 2.26	76.09 ± 2.35	157.64 ± 16.16	78.39 ± 6.41	79.16 ± 6.37	2.28 ± 0.00	12.93 ± 0.03	6.98 ± 0.17
EC1KD2	16.67 ± 1.67	85.84 ± 1.58	81.81 ± 3.37	204.71 ± 2.35	97.81 ± 7.25	102.72 ± 2.82	2.36 ± 0.02	11.20 ± 0.10	6.29 ± 0.17
EC1KD3	12.00 ± 1.73	99.72 ± 3.74	86.25 ± 2.15	213.56 ± 3.80	80.59 ± 3.03	80.94 ± 1.70	2.49 ± 0.01	13.40 ± 0.10	5.60 ± 0.11
EC1KD4	19.67 ± 5.24	91.96 ± 7.34	83.12 ± 5.29	262.98 ± 16.40	110.87 ± 10.80	114.88 ± 10.75	2.29 ± 0.00	13.03 ± 0.13	12.16 ± 0.38
EC2KD1	9.67 ± 0.88	89.78 ± 2.99	84.77 ± 3.05	206.71 ± 11.47	82.28 ± 0.94	94.04 ± 6.04	2.39 ± 0.01	12.30 ± 0.06	4.49 ± 0.26
EC2KD2	17.33 ± 0.33	91.17 ± 3.15	82.86 ± 3.34	205.24 ± 20.53	90.01 ± 3.90	89.00 ± 4.91	2.30 ± 0.00	10.03 ± 0.09	18.16 ± 0.55

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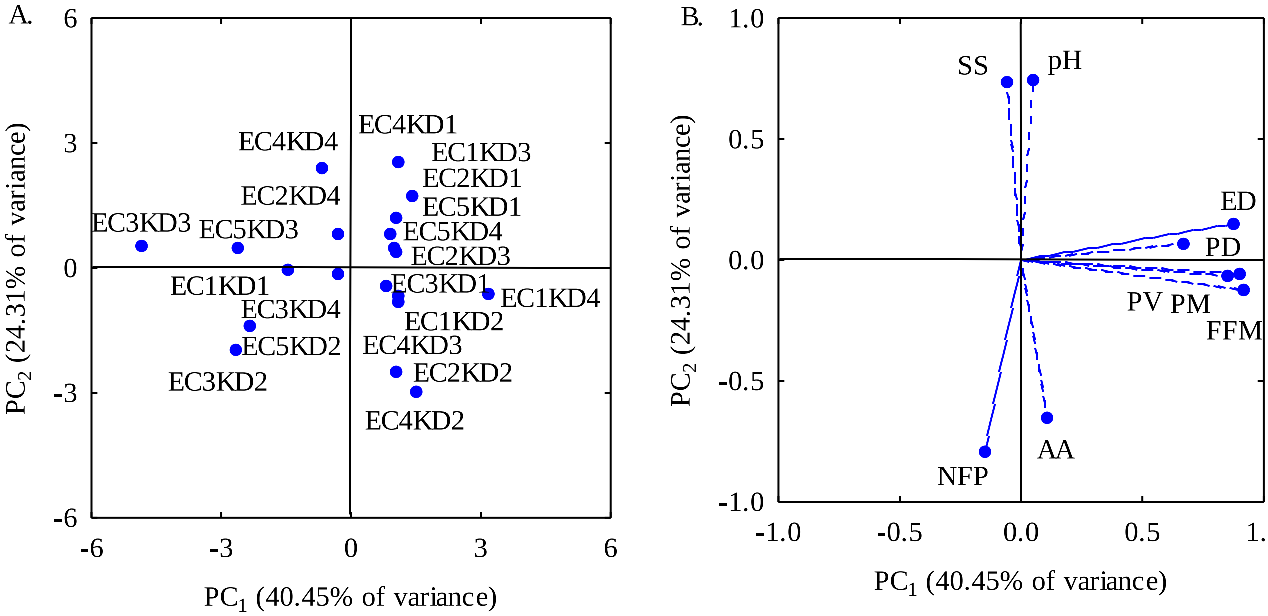
TREAT	Mean values								
	NFP	PD	ED	FFM	PM	PV	pH	SS	AA
EC2KD3	11.67 ± 2.67	97.09 ± 3.52	84.65 ± 3.17	201.07 ± 5.96	82.41 ± 2.29	82.70 ± 0.92	2.33 ± 0.07	11.73 ± 0.03	5.64 ± 0.42
EC2KD4	9.00 ± 1.53	88.86 ± 2.21	78.01 ± 0.55	175.17 ± 7.52	83.55 ± 2.00	81.50 ± 3.75	2.40 ± 0.01	11.13 ± 0.20	5.65 ± 0.30
EC3KD1	15.33 ± 0.33	88.28 ± 2.91	83.39 ± 3.07	229.82 ± 7.09	84.60 ± 3.50	86.67 ± 4.14	2.21 ± 0.01	13.57 ± 0.03	5.85 ± 0.14
EC3KD2	13.00 ± 0.58	85.16 ± 7.21	75.98 ± 5.74	163.90 ± 4.05	53.46 ± 0.21	58.75 ± 0.72	2.23 ± 0.03	8.63 ± 0.03	4.16 ± 0.10
EC3KD3	15.33 ± 0.88	74.95 ± 6.17	67.33 ± 3.83	108.57 ± 5.42	52.59 ± 4.53	52.75 ± 4.76	2.38 ± 0.01	14.03 ± 0.03	7.43 ± 0.14
EC3KD4	11.67 ± 0.33	83.48 ± 3.05	79.13 ± 3.88	180.75 ± 9.75	99.11 ± 7.62	74.64 ± 7.43	2.29 ± 0.00	12.27 ± 0.03	8.43 ± 0.37
EC4KD1	4.67 ± 0.33	84.53 ± 1.62	82.52 ± 3.22	198.81 ± 18.28	98.63 ± 5.73	99.08 ± 6.60	2.40 ± 0.00	14.90 ± 0.00	6.22 ± 0.04
EC4KD2	15.67 ± 0.67	87.61 ± 2.22	80.84 ± 5.66	206.46 ± 21.21	103.41 ± 3.50	103.78 ± 3.92	2.28 ± 0.00	9.47 ± 0.42	18.27 ± 0.40
EC4KD3	14.00 ± 5.65	82.15 ± 2.92	76.70 ± 2.71	219.27 ± 12.65	109.54 ± 6.62	108.50 ± 6.06	2.28 ± 0.04	11.37 ± 0.07	5.77 ± 0.18
EC4KD4	6.33 ± 0.88	86.06 ± 1.90	78.17 ± 2.25	157.53 ± 13.51	80.54 ± 3.38	82.63 ± 3.68	2.57 ± 0.03	12.33 ± 0.12	6.78 ± 0.37
EC5KD1	12.00 ± 1.15	83.92 ± 1.08	85.97 ± 5.77	177.81 ± 18.56	98.26 ± 15.61	95.50 ± 9.88	2.46 ± 0.00	11.27 ± 0.09	5.48 ± 0.25
EC5KD2	11.33 ± 0.88	80.04 ± 0.74	72.16 ± 0.26	148.51 ± 0.37	70.45 ± 4.51	70.46 ± 5.03	2.30 ± 0.10	10.73 ± 0.03	17.31 ± 0.46
EC5KD3	13.00 ± 1.73	80.40 ± 2.90	71.71 ± 1.44	157.39 ± 14.94	67.37 ± 1.86	67.08 ± 2.01	2.37 ± 0.01	12.53 ± 0.12	5.26 ± 0.14
EC5KD4	13.67 ± 2.73	82.29 ± 4.43	82.66 ± 3.62	227.34 ± 17.52	92.47 ± 18.51	96.25 ± 17.18	2.49 ± 0.01	11.33 ± 0.03	5.81 ± 0.00

KD-potassium dose, KD1-60% of the recommendation; KD2-80% of the recommendation; KD3-100% of the recommendation; KD4-120% of the recommendation; ±-standard deviation; NFP-number of fruits per plant, PD-polar diameter (mm); ED-equatorial diameter (mm); FFM-fresh fruit mass (g per plant); PM-pulp mass (g); PV-pulp volume (mL); pH-hydrogen potential; SS-soluble solids; AA-ascorbic acid (mg $100g^{-1}$ of pulp).

Figures 1A and 1B illustrate the impact of the treatments and variables on the first and second principal components (PC1 and PC2) respectively. PC1 represents a potential interaction between the electrical conductivity levels of the irrigation water and the potassium doses (ECw × KD). The correlation coefficients for the polar diameter, equatorial diameter, fresh fruit mass, pulp mass, and pulp volume were all 0.66 or greater.



KD-potassium fertilization dose, KD1 (60% of the K recommendation); KD2 (80% of the K recommendation); KD3 (100% of the K recommendation); KD4 (120% of the K recommendation).

Figure 1. Two-dimensional projection of the scores of the principal components for the factors levels of electrical conductivity of water—EC and genotypes of sour passion fruit (A) and the variables analyzed (B) in the two principal components (PC1 and PC2).

The treatments that received a potassium dose equivalent to 100% of the recommendation [18] and an electrical conductivity of the irrigation water of 0.3 dS m^{-1} (EC1KD3) showed the largest diameters, both polar and equatorial, with values of 99.72 mm and 86.25 mm, respectively (Table 2). On the other hand, the plants that received K fertilization equivalent to 100% of the K recommendation and an ECw of 1.9 dS m^{-1} (EC3KD3) had the lowest values for both diameters. A reduction of 24.84% in the polar diameter and 21.93% in the equatorial diameter was observed when comparing the treatments EC1KD3 and EC3KD3. This suggests that increasing the potassium dose did not counteract the negative effects of salt stress on the physical parameters of the sour passion fruits. The presence of excess salts in the soil solution severely hindered the absorption of water and nutrients by the plants, which can have detrimental effects on the growth, production, and quality of the crops [32]. In a study on the production and postharvest quality of sour passion fruits irrigated with saline waters (0.6 to 3.0 dS m^{-1}) and treated with exogenous application of H_2O_2 (0, 15, 30, and 45 µM), [33] also observed a reduction in the equatorial and polar diameters of the fruits with increase in electrical conductivity of the water.

The FFM, PM, and PV values were highest when the plants were fertilized with a dose equivalent to 120% of the K recommendation and irrigated with water of 0.3 dS m^{-1} (EC1KD4). This resulted in 262.98 g per plant, 110.87 g, and 114.88 mL, respectively. On the other hand, the lowest values were obtained when the plants were irrigated with water of 1.9 dS m^{-1} under K fertilization with 100% of the recommendation (EC3KD3), resulting in 108.57 g per plant, 52.59 g, and 52.75 mL, respectively. Comparing the EC3KD3 treatment to the EC1KD4 treatment, there were reductions of 58.71% (154.41 g per plant) in the FFM, 52.56% (58.28 g) in the PM, and 54.08% (62.43 g) in the PV of the cultivated plants (Table 2). The FFM, PM, and PV increased with higher K fertilization when the plants were cultivated with water of low electrical conductivity (0.3 dS m^{-1}). However, there was no attenuating effect of potassium observed when plants were cultivated under the highest electrical conductivity levels of the irrigation water. This lack of effect may be due to the high salt index (46%) of the fertilizer used (potassium sulfate) in the experiment, which can intensify the effects of salinity and compromise the absorption of calcium and magnesium by the plants [34]. The FFM reflects the net accumulation of water in the fruit, as it is influenced by water inflow and outflow as well as photosynthetic products [35].

The reductions in FFM, PM, and PV are likely caused by the effects of salinity, which restrict water and nutrient uptake by the roots, leading to losses in production parameters under stress conditions [36]. In a separate study, [33] also observed a reduction in the FFM of the sour passion fruit with increasing electrical conductivity levels of the irrigation water (0.6 to 3.0 dS m^{-1}) in the first crop cycle under protected environmental conditions. The data for the PC2 indicated that the eigenvalues were 0.65 or above for the number of fruits per plant, pH, soluble solids, and ascorbic acid (Table 3).

The plants that received water with an ECw of 0.3 dS m^{-1} and were fertilized with 120% of the recommended K dose had the highest number of fruits per plant, reaching 19.67 fruits per plant. This was 321.2% higher than the yield of plants grown under an ECw of 2.7 dS m^{-1} (4.67 fruits per plant) and fertilized with 60% of the recommended potassium dose (EC4KD1). The highest fruit yield was observed when plants were irrigated with water of the lowest ECw in combination with the highest K dose (120% of the recommended amount).

Under conditions of salt stress, various physiological processes such as photosynthesis, lipid metabolism, hormonal regulation, enzymatic activity, and protein synthesis were adversely affected. Osmotic stress and ion toxicity led to oxidative stress reactions involving reactive oxygen species (ROS), resulting in lipid peroxidation of membranes and proteins, and in severe cases, cell death [37, 38]. A study by [39] on sour passion fruit cultivation with saline water (0.3 to 3.5 dS m^{-1}) of different cationic compositions revealed that the highest fruit yield (11.33 fruits) was achieved with water of low electrical conductivity (0.3 dS m^{-1}). Furthermore, the research indicated that an increase in ECw had a negative impact on the number of sour passion fruit plants, irrespective of the cationic nature.

In terms of pH, the fruits from plants grown under an electrical conductivity of 2.7 dS m^{-1} and a potassium dose of 120% of the K recommendation (EC4KD4) recorded the highest value of.57. Conversely, the lowest pH value of 2.21 was observed in the fruit pulp from plants irrigated with water of 1.9 dS m^{-1} and fertilized with 60% of the K (EC3KD1), resulting in a 14% decrease (0.36 units) compared to the treatment with the highest pH value (EC4KD4) (Table 2). These pH values are lower than those reported by [40], who found an average pH of 3.00 in the fruit pulp of the sour passion fruit accession 'Guinezinho' grown with biofertilizer and saline water (4.45 dS m^{-1}).

The highest soluble solids (SS) content of 14.90 ºBrix was observed in the fruits from plants irrigated with water of 2.7 dS m^{-1} and fertilized with 60% of the K recommendation (Table 2). On the other hand, the lowest SS content of 8.63 ºBrix was observed when plants were irrigated with water of 1.9 dS m^{-1} and fertilized with 80% of the K (EC3KD2). It is worth noting that only treatments with ECw levels of 1.1, 1.9, 2.7, and 3.5 dS m^{-1}, in combination with 80% of the K recommendation, did not meet the minimum commercialization requirement of 11 °Brix set by the Brazilian Ministry of Agriculture, Livestock, and Food Supply [41]. This suggests that fruits from other treatments in this study have suitable quality for commercial purposes.

The ascorbic acid (AA) contents showed the lowest value (4.16 mg $100g^{-1}$ of pulp) when irrigated with water of 1.9 dS m^{-1} and fertilized with 80% of the recommended K dose (EC3KD2), which was also observed for the pulp pH (Table 2). On the other hand, the highest value (18.27 mg $100g^{-1}$ of pulp) was found in plants irrigated with water of 2.7 dS m^{-1} and fertilized with KD equivalent to 80% of the K (EC4KD2). The results for AA followed the same trend as that of soluble solids (Table 2), indicating that the synthesis of AA (vitamin C) is influenced by the contents of sugar present in the fruit pulp. The fruits synthesize AA from hexose sugars, specifically D-glucose or D-galactose [42,43].

The Pearson correlation matrix (Figure 2) presents the changes in post-harvest production behavior and quality variables.

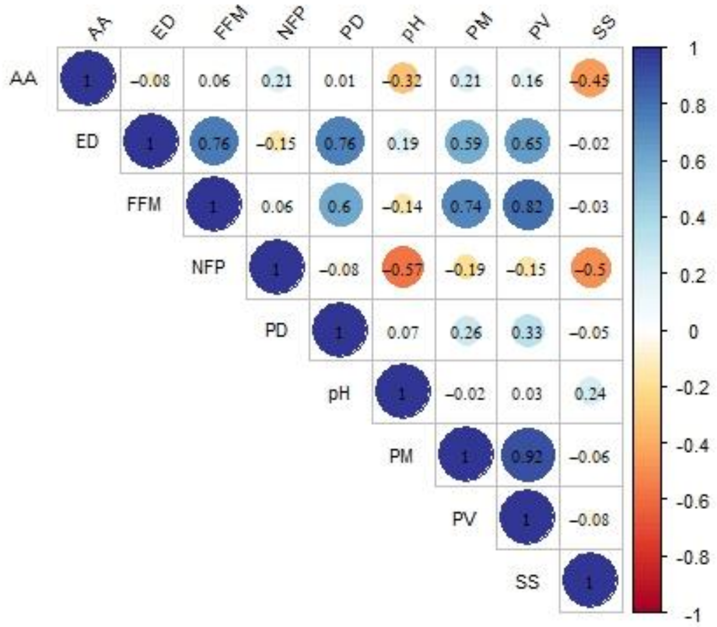


Figure 2. Pearson correlation matrix for the variables analyzed within the electrical conductivity levels of irrigation water and potassium fertilization of the sour passion fruit.

The equatorial diameter (ED) shows a positive correlation with the PM (0.59), PD (0.76), FFM (0.76), and PV (0.65). Additionally, a strong positive correlation was observed between the FFM and the PM (0.74) as well as PV (0.82). The PM exhibited a strong correlation with the PV of the sour passion fruit irrigated with saline water (0.92). On the other hand, pH displayed a negative correlation with the number of fruits per plant (−0.57), which was also observed in the relationship between AA content and SS (−0.45) as well as pH (−0.32).

3.2. Univariate analysis—regression analysis

The interaction between the factors (ECw × KD) had a notable impact on all the variables examined in the pulp of sour passion fruit 160 days post-transplantation (Table 3).

The sour passion fruit exhibited varying levels of titratable acidity (TA) as shown in Figure 3A. The highest estimated values of 5.66%, 4.94%, 5.45%, and 5.91% were recorded when the plants received fertilization with doses of 60%, 80%, 100%, and 120% of the recommended dose of potassium and the irrigation was carried out with ECw of 1.5, 1.8, 1.9, and 0.3 dS m^{-1}, respectively.

According to a study [44], the ideal acidity range for consuming fresh passion fruit or its pulp is between 2.5% and 4.6%. Therefore, the maximum values observed in this research exceeded the optimal range recommended for consuming sour passion fruit pulp. On the other hand, as mentioned in [45], high titratable acidity is beneficial for the industrial sector as it reduces the need for adding acidifiers and enhances the nutritional and sensory qualities of the products.

Table 3. Summary of the analysis of variance for titratable acidity (TA), total sugars (TS), soluble solids to titratable acidity ratio (SS/TA), and pulp yield (PY), in the fruit pulp of 'BRS Sol do Cerrado' sour passion fruit cultivated under irrigation water salinity and potassium fertilization.

Sources of variation	DF	Mean squares			
		TA	TS	SS/TA	PY
Electrical conductivity (ECw)	4	101.61**	49.62**	0.002**	120.48*
Linear Regression	1	272.55**	12.86**	0.004**	190.61*
Quadratic Regression	1	50.23**	0.03ns	0.004**	4.28ns
Potassium doses (KD)	3	476.55**	48.40**	0.002**	34.79ns
Linear Regression	1	97.11**	18.24**	0.006**	3.04ns
Quadratic Regression	1	506.63**	20.61**	0.001**	99.61ns
Interaction (ECw × KD)	12	154.78**	29.05**	0.01**	142.31**
Block	2	1.02	0.13	0.00	25.42
Residual	38	1.42	0.10	0.00	45.52
CV (%)		2.47	3.30	3.55	14.75

DF-degrees of freedom; CV (%)-coefficient of variation; * significant at 0.05 probability level; ** significant at 0.01 probability level; ns not significant, by the F test ($p > 0.05$).

Pinheiro and collaboladores [46] assessed the postharvest quality of sour passion fruit grown under different irrigation strategies with brackish water. The study evaluated the effects of various irrigation management strategies, including SE-irrigation with water of 1.3 dS m^{-1} throughout the growth cycle, irrigation with water of 4.0 dS m^{-1} during specific stages such as the vegetative stage (VE), flowering stage (FL), fruiting stage (FR), and successively in the vegetative/flowering stages (VE/FL), and vegetative/fruiting stages (VE/FR). Additionally, two different potassium doses (KDs) were applied, representing 60% and 100% of the recommendation. The results showed that plants fertilized with 60% of the recommended potassium dose and subjected to high-salinity water during the VE/FL stages exhibited an increase in the titratable acidity of the fruit pulp.

In terms of total sugars (TS) content (Figure 3B), plants fertilized with KDs of 80% and 100% of the recommended dose obtained the highest estimated values, with 12.70 and 13.69 mg 100g^{-1} of pulp under ECw of 3.5 and 0.3 dS m^{-1}, respectively. On the other hand, plants fertilized with 120% of the recommended potassium dose showed a linear reduction in total sugar content, with a decrease of 70.56% (2.63 mg 100g^{-1} of pulp) between the lowest and highest ECw levels. The data related to the fertilization with 60% of the K recommendation were not adequately described by the regression models studied, but the mean value of total sugar content was found to be 10.4 mg 100g^{-1} of pulp.

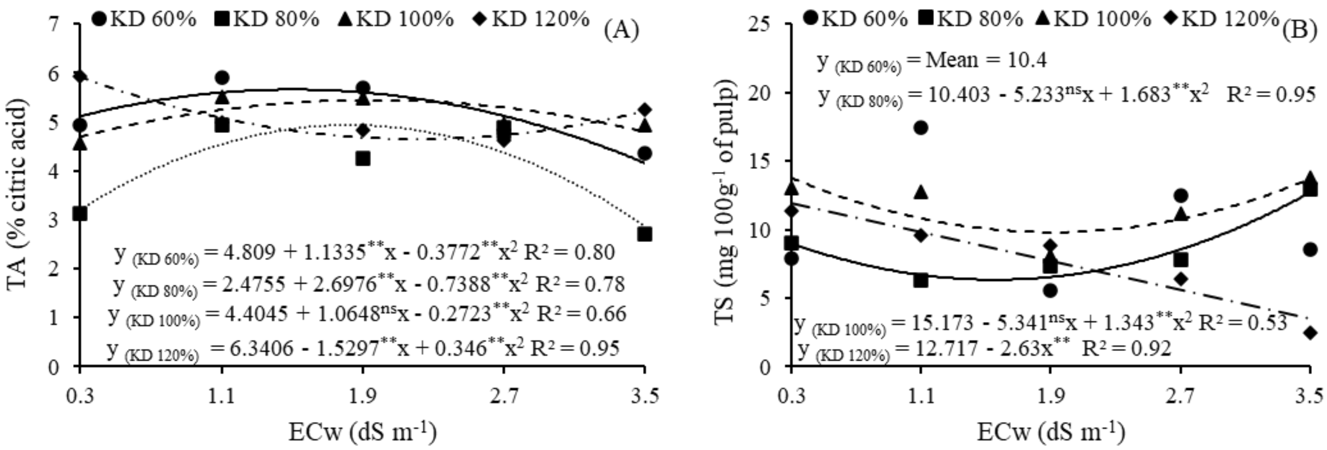


Figure 3. Titratable acidity-TA (A) and total sugars-TS (B) of fruits of 'BRS Sol do Cerrado' sour passion fruit as a function of the interaction between the electrical conductivity of irrigation water-ECw and potassium doses-KD. ^{ns}, **, and * represent, respectively, non-significant, significant at $p \leq 0.01$, and significant at $p \leq 0.05$ by the F test.

The results obtained in the present assay regarding the 80% K dose are in line with the results observed by [46] who studied the impact of K fertilization (60% and 100% of the recommended K dose) on sour passion fruit under different saline water irrigation strategies. It was reported that plants which received 60% K fertilization and were irrigated with water of 4.0 dS m^{-1} during the fruiting phase exhibited the highest total sugar levels in the fruits.

Moreover, a decline in total sugar content was observed with an increase in the ECw when utilizing 100% and 120% of the recommended K dose. This decrease is likely linked to the positive effects of potassium, as the response mechanism to salt stress is greatly influenced by the potassium content within the cells. Potassium is crucial for protein synthesis and sugar transportation in the phloem of plants [47].

In terms of the SS/TA ratio (Figure 4A), the highest estimated values of 3.34% and 3.66% were recorded in plants that were fertilized with 60% and 80% of the recommended K dose, and irrigated with water measuring 3.5 dS m^{-1}, respectively. Conversely, when plants were fertilized with 100% and 120% of the recommended dose of K, the highest estimated values (2.77% and 2.48%, respectively) were achieved when the plants were cultivated under ECw levels of 0.3 and 2.0 dS m^{-1}, respectively.

The SS/TA ratio is a parameter that determines the sweet-acidic nature and is regarded as a rapid method to assess the flavor of fruits [48]. A decrease in the SS/TA ratio is caused by the decrease in soluble solids content and/or an increase in titratable acidity, resulting from the impact of organic acids [49]. Additionally, various factors like crop growing conditions and fruit maturity stage can significantly affect the SS/TA ratio [50].

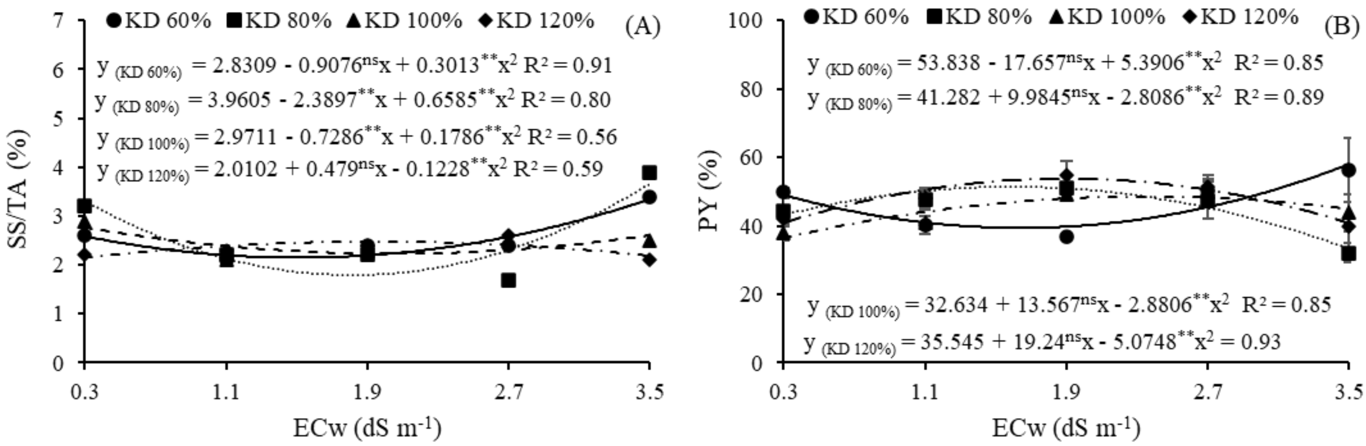


Figure 4. Ratio between soluble solids content and titratable acidity-SS/TA (A) and pulp yield-PY (B) in fruits of 'BRS Sol do Cerrado' sour passion fruit as a function of the interaction between the electrical conductivity of irrigation water (ECw) and potassium doses (KD). ^{ns}, **, and * represent, respectively, non-significant, significant at $p \leq 0.01$, and significant at $p \leq 0.05$ by the F test.

In terms of pulp yield (Figure 4B), the plants that received fertilization with 60, 80, 100, and 120% of the recommended K dose achieved maximum estimated values of 58.07, 50.15, 48.60, and 53.78%, respectively under ECw levels of 3.5, 1.8, 2.4, and 1.9 dS m^{-1}. It is worth noting that the relatively low pulp yield observed in this study may be attributed to the fact that, under salt stress conditions, the plant tends to allocate energy towards seed formation to ensure species propagation. Consequently, this leads to a greater accumulation of aril, which is the substance surrounding passion fruit seeds and is the part of greatest economic importance for the species.

Assessing the production and postharvest quality of sour passion fruit irrigated with saline water (0.6 to 3.0 dS m^{-1}) and subjected to exogenous H_2O_2 application (0, 15, 30, and 45 μM), [33] noted a positive correlation between PY and ECw. The highest PY value (70.54%) was recorded in plants irrigated with water of 3.0 dS m^{-1} in the absence of H_2O_2 application.

4. Conclusions

The FFM of the 'BRS Sol do Cerrado' sour passion fruit decreased as the dose of K fertilizer was reduced and the electrical conductivity levels of the irrigation water increased.

The sour passion fruit exhibited an increase in contents of total soluble solids and ascorbic acid when irrigated with water of an electrical conductivity of 2.7 dS m^{-1} and fertilized with 60 and 80% of the recommended K dose.

Irrigation with water having an electrical conductivity of 3.5 dS m^{-1} and application of 60% of the potassium resulted in an increase in the pulp yield of the sour passion fruit 160 days after transplantation.

Use of AI tools declaration

The authors declare that they did not use Artificial Intelligence (AI) tools in the preparation of this article.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

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