e-ISSN 1983-4063 - *www.agro.ufg.br/pat* - Pesq. Agropec. Trop., Goiânia, v. 54, e80305, 2024

Research Article

Silicon as a salt stress mitigator in yellow passion fruit seedlings[1]

Cristóvão Jacques de Sousa Almeida[2], Jussara Silva Dantas[3], Evandro Franklin de Mesquita[4], Caio da Silva Sousa[2], Vitória Carolina da Silva Soares[4], José Paulo Costa Diniz[2], Rennan Fernandes Pereira[4], Lays Klécia Silva Lins[4], Virgínia de Fátima Bezerra Nogueira[2], Irinaldo Pereira da Silva Filho[4]

ABSTRACT

In the Brazilian semi-arid region, the production of passion fruit seedlings often faces challenges such as irrigation with saline water. However, silicate fertilization stands out as an effective solution for mitigating the salinity effects. This study aimed to evaluate the use of silicon as a salt stress mitigator in yellow passion fruit seedlings, under greenhouse conditions. The experimental design was completely randomized, with six replications, in a 5 × 2 factorial scheme, referring to five silicon doses (0, 0.25, 0.50, 0.75 and 1.0 g plant^{-1}) and two electrical conductivity levels of the irrigation water (1.2 and 3.5 dS m^{-1}). Variables related to plant growth, biomass and physiology were analyzed. Silicon doses between 0.50 and 0.60 g plant^{-1} provided the best results for the passion fruit seedlings' growth, water status and physiology, both under lower (1.2 dS m^{-1}) and higher (3.5 dS m^{-1}) salinity conditions. The silicon strengthened the plants and improved water absorption, mitigating the negative effects of salinity on the yellow passion fruit.

KEYWORDS: *Passiflora edulis* Sims., salinity, silicate fertilization.

RESUMO

Silício como atenuante do estresse salino em mudas de maracujazeiro-amarelo

No semiárido brasileiro, a produção de mudas de maracujazeiro, muitas vezes, enfrenta desafios como a ocorrência de águas salinas para irrigação. Porém, a adubação silicatada tem se destacado como solução eficaz para mitigar os efeitos da salinidade. Objetivou-se avaliar o uso de silício como atenuante do estresse salino em mudas de maracujazeiro-amarelo, em estufa agrícola. O delineamento foi inteiramente casualizado, com 6 repetições, em arranjo fatorial 5 × 2, referente a cinco doses de silício (0; 0,25; 0,50; 0,75; e 1,0 g planta^{-1}) e dois níveis de condutividade elétrica da água de irrigação (1,2 e 3,5 dS m^{-1}). Foram analisadas variáveis relacionadas ao crescimento, biomassa e fisiologia das plantas. Doses entre 0,50 e 0,60 g planta^{-1} de silício proporcionaram melhores resultados no crescimento, status hídrico e fisiologia das mudas de maracujá, tanto em condições de salinidade mais baixa (1,2 dS m^{-1}) quanto mais elevada (3,5 dS m^{-1}). O silício fortaleceu as plantas e melhorou a absorção de água, atenuando os efeitos negativos da salinidade no maracujazeiro-amarelo.

PALAVRAS-CHAVE: *Passiflora edulis* Sims., salinidade, adubação silicatada.

INTRODUCTION

Yellow passion fruit (*Passiflora edulis* Sims.) is a tropical fruit tree of great economic value. It is known for its fruit quality and nutraceutical properties, and provides a quick economic return due to its high yield (Mesquita et al. 2024, Weyya et al. 2024). Brazil, with its favorable climate and vast availability of arable lands, is the world's leading passion fruit producer, consumer and exporter, with the Northeast region standing out as the country's largest producer (Costa et al. 2023, IBGE 2024).

In the Northeast region of Brazil, where the semi-arid climate predominates with long periods of drought and high evapotranspiration and temperature indexes, the passion fruit production depends on irrigation. However, the high salt concentrations in surface and groundwater used for this purpose

---

[1] Received: Aug. 27, 2024. Accepted: Nov. 25, 2024. Published: Dec. 18, 2024. DOI: 10.1590/1983-40632024v5480305.

[2] Universidade Federal de Campina Grande, Pombal, PB, Brazil. *E-mail/ORCID*: jacquessalmei@hotmail.com/0009-0003-1768-6694; caiosilvafla16@gmail.com/0000-0002-4163-8313; josepaulo.rc06@gmail.com/0000-0002-9247-8970; virginia.fatima@professor.ufcg.edu.br/0000-0002-5564-1011.

[3] Universidade Federal de Campina Grande, Patos, PB, Brazil. *E-mail/ORCID*: jussara.silva@professor.ufcg.edu.br/0000-0001-5539-0366.

[4] Universidade Estadual da Paraíba, Catolé do Rocha, PB, Brazil. *E-mail/ORCID*: evandrofranklin@servidor.uepb.edu.br/0000-0001-5722-2235; vitoria.16carolina@gmail.com/0000-0002-1519-1853; rennan.fp@gmail.com/0000-0002-2994-3737; layslins@servidor.uepb.edu.br/0000-0001-8074-7291; irinaldo@servidor.uepb.edu.br/0009-0009-9046-3992.

often compromise the crop yield (Lima et al. 2021, Silva et al. 2021). Therefore, increasing the passion fruit tolerance to salinity is a major challenge for agriculture in that region (Lima et al. 2023).

Seedling production is one of the most important stages in the passion fruit production cycle. Quality seedlings are known to result in productive and profitable orchards. Efficient techniques that minimize the adverse effects of abiotic factors, such as salt stress, and increased crop yield are crucial (Melo et al. 2019).

Silicon is a promising alternative for reducing the impact of salinity on plant growth and yield (Liu et al. 2019, Singh et al. 2023), and its application during seedling formation can increase the plant tolerance to excess salts by reducing the absorption of sodium ions (Na^+) due to root silicification, improving the plant's structural properties (Cassel et al. 2021, Irfan et al. 2023). Furthermore, silicon helps to maintain water balance, stabilize cell membranes, antioxidant activity and essential element absorption, improving aspects related to plant physiology and growth (Liu et al. 2019, Mandlik et al. 2020, Singh et al. 2023).

In recent years, some studies have demonstrated the benefits of silicon for passion fruit as a salt stress mitigator (Diniz et al. 2020a, Diniz et al. 2020b, Diniz et al. 2021, Sá et al. 2021). However, despite the progress made, the literature still lacks information on the specific effects of silicon on this species' seedlings, particularly in semi-arid environments. Therefore, this study aimed to evaluate the use of silicon to mitigate salt stress in yellow passion fruit seedlings, in the semi-arid region of Brazil.

MATERIAL AND METHODS

The experiment was conducted in a protected environment at the Universidade Estadual da Paraíba, in Catolé do Rocha, Paraíba state, Brazil, between February and April 2023. The municipality is located in the semi-arid region of the Paraíba backlands (6º20'38"S, 37º44'48"W and altitude of 275 m), which has a hot semi-arid Bsh climate, according to the Köppen classification (Alvares et al. 2013). Figure 1 shows the climatic data recorded in the greenhouse during the experiment.

The BRS Gigante Amarelo yellow passion fruit cultivar was used, and sowing occurred in polyethylene trays with 200 cells, each with a volume of 0.0125 dm^3, filled with a mixture of organic compost (worm humus) and soil material (1:1). At 15 days after sowing (DAS), the most vigorous seedlings with a pair of definitive leaves were selected to transplant into polyethylene bags with capacity of 3.0 dm^3, containing substrate composed of topsoil (0-0.2 m) and tanned cattle manure (1:1). Table 1 shows the characteristics of the soil material used.

The cattle manure characteristics were: pH (H_2O) = 7.7; electrical conductivity = 6.09 dS m^{-1}; organic matter = 36.2 dag kg^{-1}; organic carbon = 166.9 g kg^{-1}; N = 13.9 g kg^{-1}; C/N ratio = 12; P = 3.2 $cmol_c$ dm^{-3}; K^+ = 18.7 $cmol_c$ dm^{-3};

Table 1. Chemical and physical composition of the soil used in the experiment.

Chemical attributes		Physical attributes	
pH	6.00	Sand (g kg^{-1})	831.50
P (mg dm^{-3})	16.63	Silt (g kg^{-1})	100.00
K^+ ($cmol_c$ dm^{-3})	0.08	Clay (g kg^{-1})	68.50
Ca^{2+} ($cmol_c$ dm^{-3})	1.09	CDW (g kg^{-1})	0.00
Mg^{2+} ($cmol_c$ dm^{-3})	1.12	DF (g dm^{-3})	1.00
Na^+ ($cmol_c$ dm^{-3})	0.05	SD (g cm^{-3})	1.53
SB ($cmol_c$ dm^{-3})	2.34	PD (g cm^{-3})	2.61
$H^+ + Al^{3+}$ ($cmol_c$ dm^{-3})	1.24	TP (m^3 m^{-3})	0.42
Al^{3+} ($cmol_c$ dm^{-3})	0.00	H0.01MPa (g kg^{-1})	65.00
CEC ($cmol_c$ dm^{-3})	3.58	H0.03MPa (g kg^{-1})	49.00
V (%)	65.36	H1.50MPa (g kg^{-1})	28.00
OM (g kg^{-1})	13.58	Textural class	SCL
Si (mg dm^{-3})	29.00		

SB: sum of exchangeable bases (SB = $Ca^{2+} + Mg^{2+} + K^+ + Na^+$); CEC: cation exchange capacity [CEC = SB ($Ca^{2+} + Mg^{2+} + K^+ + Na^+$)]; V: soil saturation by exchangeable bases [V = (SB/CEC) × 100]; OM: soil organic matter; CDW: clay dispersed in water; DF: degree of flocculation {DF = [(clay - CDW)/clay] × 100}; SD and PD: soil and particle density, respectively; TP: total porosity (soil macro and microporosity); SCL: sandy clay loam; H: soil humidity.

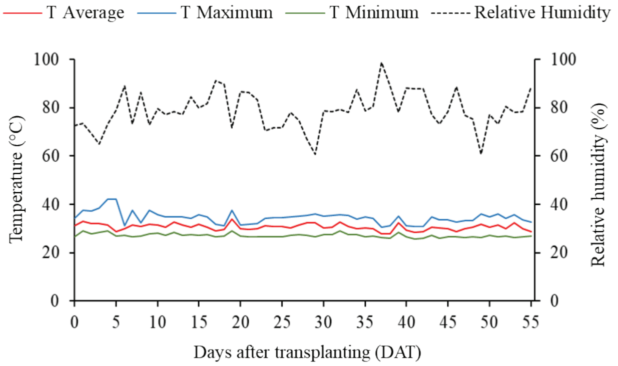


Figure 1. Data on average, maximum and minimum temperature (T), and relative humidity throughout the experiment, between February and April 2023 (Catolé do Rocha, Paraíba state, Brazil).

Ca^{2+} = 16.2 $cmol_c$ dm^{-3}; Mg^{2+} = 6.1 $cmol_c$ dm^{-3}; S = 2.5 $cmol_c$ dm^{-3}; CEC = 133.9 mmol dm^{-3}; B = 14.8 mg kg^{-1}; Fe = 11,129.9 mg kg^{-1}; Cu = 19.3 mg kg^{-1}; Mn = 491.4 mg kg^{-1}; Zn = 65.3 mg kg^{-1}; Si (Embrapa 2009) = 12.5 g kg^{-1}; Na^+ = 3.5 g kg^{-1}.

The experimental design was completely randomized, with six replications, in a 5 × 2 factorial scheme, referring to five silicon doses (0, 0.25, 0.50, 0.75 and 1.0 g $plant^{-1}$) and two electrical conductivity levels of the irrigation water (1.2 and 3.5 dS m^{-1}). Silicon was applied via fertigation using silicic acid as a source (Costa et al. 2016b, Almeida et al. 2006). The chemical composition of this acid is 92 % of SiO_2, 42.9 % of Si, an apparent density between 80 and 140 g L^{-1}, particle size between 8 and 12 μm and pH between 6.0 and 7.5. There were two silicon applications: the first occurred when the seedlings were transplanted into polyethylene bags, and the second at 30 days after transplanting (DAT). The total dose was divided equally between the two applications.

The salinized water was prepared by dissolving sodium chloride (NaCl) in well water, which had the following characteristics: pH = 6.9; K^+ = 21 $mmol_c$ L^{-1}; Ca^{2+} = 2.5 $mmol_c$ L^{-1}; Mg^{2+} = 1.48 $mmol_c$ L^{-1}; Na^+ = 6.45 $mmol_c$ L^{-1}; Cl^- = 8.1 $mmol_c$ L^{-1}; HCO_{3^-} = 2.75 $mmol_c$ L^{-1}; SO_4^{2-} = 0.18 $mmol_c$ L^{-1}; sodium adsorption ratio = 4.57 $(mmol\ L^{-1})^{1/2}$.

The plants were manually irrigated daily, and, until 10 DAT, all the plants were watered with water with electrical conductivity of 1.2 dS m^{-1}. Irrigation with 3.5 dS m^{-1} water began at 11 DAT. The water volumes used in each irrigation event were defined according to the plants' water consumption, calculated using the following equation: $VI = (Vp - Vd) + LF$, where: VI (mL) is the volume of water to be applied in the next irrigation event; Vp (mL) the volume of water applied in the previous irrigation event; Vd (mL) the volume of water drained in the previous irrigation event; and LF the 10 % leaching fraction, applied every two weeks.

At 60 DAT, the following variables were analyzed: plant height, measured with a ruler in mm from the plant's neck to the insertion of the last formed leaf; and stem diameter, measured with a stainless-steel digital caliper, at the height of 1 cm in the neck region of each plant. After these measurements, the plants were separated into shoot and roots. Then, they were dried in a forced-air circulation oven at 65 ºC, until reaching a constant mass, to determine the shoot and root dry masses.

The water status, electrolyte leakage and gas exchange assessments were conducted at the day before the growth and mass partitioning analyses.

The relative water content (RWC) was estimated by the ratio among the fresh (FM), turgid (TM) and dry (DM) masses of 10 leaf disks (113 mm^2), according to the following equation (Cairo 1995): RWC = [(FM - DM)/(TM - DM)] x 100. The FM was measured immediately after collecting the leaf discs; TM after immersing the discs in 20 mL of distilled water for 24 hours; and DM after drying the samples in a forced-air circulation oven at 65 ºC, until they reached a constant mass.

For the electrolyte leakage analysis, five leaf discs (113 mm^2) were placed in containers with 20 mL of distilled water and kept at room temperature overnight. Then, the initial electrical conductivity of the medium (Ci) was measured. Afterwards, the samples were put in test tubes with lids and subjected to water bath at 100 ºC, for 60 min. Finally, the final electrical conductivity of the medium (Cf) was measured. The electrolyte leakage was determined by the ratio (Ci/Cf) x 100 (Scotti & Thi 1997).

The water-use efficiency was obtained from the ratio between the total dry matter and the total volume of water applied during the experiment.

Gas exchange assessments began at 8 a.m., using an infrared gas analyzer (IRGA), model CIRAS-3, with a constant light of 1,200 μmol m^{-2} s^{-1} of photons. The measured variables included: CO_2 assimilation rate (A), stomatal conductance (gs), transpiration (E) and internal CO_2 concentration (Ci).

The data were subjected to the Shapiro-Wilk test for normality of errors and the Bartlett's test for homogeneity of variances. Once these assumptions had been met, the data were submitted to analysis of variance using the F test. Then, the first and second-degree linear regressions were applied. Furthermore, the Pearson's correlation analysis was conducted. The statistical analyses used the packages available in the RStudio (R Core Team 2023).

RESULTS AND DISCUSSION

According to the analysis of variance (Table 2), the silicon × salt levels interaction significantly affected the plant height and stem diameter of the yellow passion fruit seedlings. On the other hand, the

Table 2. Summary of the analyses of variance for plant height (PH), stem diameter (SD), shoot dry mass (SDM), root dry mass (RDM), relative water content (RWC), electrolyte leakage (EL), water-use efficiency (WUE), CO_2 assimilation rate (*A*), stomatal conductance (*gs*), transpiration rate (*E*) and internal CO_2 concentration (*Ci*) recorded for the yellow passion fruit seedlings subjected to silicon fertilization and saline water irrigation.

Source of variation	DF	Mean square					
		PH	SD	SDM	RDM	RWC	EL
Silicon (Si)	4	2,169.58**	3.89**	3.65**	0.071**	1,003.79**	266.78**
Salt	1	5,593.14**	26.54**	22.25**	0.524**	2,640.19**	3,130.01**
Si × salt	4	306.15**	0.37**	0.22^{ns}	0.014^{ns}	147.19*	78.49*
Waste	50	24.78	0.09	0.46	0.008	44.76	30.67
CV (%)	-	13.89	6.95	26.38	25.41	9.85	18.95

Source of variation	DF	WUE	*A*	*gs*	*E*	*Ci*
Silicon (Si)	4	0.00095**	25.97**	0.013**	1.24^{ns}	3,668.10**
Salt	1	0.00541**	83.78**	0.324**	52.95**	5,152.26**
Si × salt	4	0.00007^{ns}	1.17^{ns}	0.022**	4.05**	1,256.97^{ns}
Waste	50	0.00022	5.79	0.002	0.58	542.36
CV (%)	-	30.63	21.02	18.57	12.36	8.58

^{ns} Not significant; * significant at $p \leq 0.05$; ** significant at $p \leq 0.01$; DF: degrees of freedom; CV: coefficient of variation.

shoot and root dry mass showed significant effects of the factors silicon and salt levels in isolation. Regarding the variables related to the plants' cellular status, the analyses of variance revealed significant effects of the silicon × salt levels interaction for relative water content and electrolyte leakage. Conversely, the water-use efficiency was significantly affected by the two factors in isolation. For the gas exchange variable, there was a significant effect of the silicon × salt levels interaction for stomatal conductance and transpiration. For the CO_2 assimilation rate and the internal CO_2 concentration, the F test ($p \leq 0.01$) showed isolated effects of the factors Si and salt levels.

The plant height fitted a quadratic regression model, where the highest value (64.50 cm) was obtained with the addition of 0.52 g plant^{-1} of silicon, under salinity of 1.2 dS m^{-1}, corresponding to a 170 % increase in height, when compared to plants that did not receive silicon supplementation (Figure 2A). When the plants were subjected to salinity of 3.5 dS m^{-1}, the greatest height (34.76 cm) occurred with the addition of 0.54 g plant^{-1} of silicon, representing an increase of 128.87 % in plant height, when compared to the plants that did not receive silicon. This increase can be explained by the deposition of silicon in the cell walls, which provides the cells with greater rigidity and firmness. It improves plant adaptation to saline conditions and promotes a better growth (Jesus et al. 2018).

The stem diameter results fitted best the quadratic regression model, both for the plants subjected to the salt level of 1.2 dS m^{-1} and those subjected to 3.5 dS m^{-1}, with the highest values of 5.19 and 4.17 mm obtained with optimum doses of 0.64 and 0.60 g plant^{-1} of silicon, respectively (Figure 2B). The benefits observed in plant growth due to silicon can be attributed to this element's protective action on cell membranes, osmotic regulation and improving the plants' ability to maintain the photosynthetic activity under stressful conditions (Rios et al. 2017). These factors contribute to a greater synthesis of photoassimilates and, consequently, a superior vegetative growth (Diniz et al. 2020a).

These results agree with those observed by Nascimento et al. (2017) and Lima et al. (2021), who observed sharp reductions in the stem diameter of passion fruit seedlings due to increases in the electrical conductivity of water levels in the irrigation water, which ranged from 0.43 to 4.5 dS m^{-1} and from 0.3 to 3.5 dS m^{-1}, respectively. Furthermore, Costa et al. (2016a) showed that the application of silicon to yellow passion fruit seedlings under saline stress mitigates the inhibition of stem diameter growth caused by salinity.

Moreover, the shoot dry mass showed a quadratic effect as a function of the silicon doses. The dose of 0.57 g plant^{-1} of silicon gave an estimated maximum value of 3.13 g, representing an increase of 74.83 %, when compared to the shoot dry mass without silicon application (Figure 2C). These results indicate that this element can improve the plant biomass accumulation, promoting a more robust plant growth.

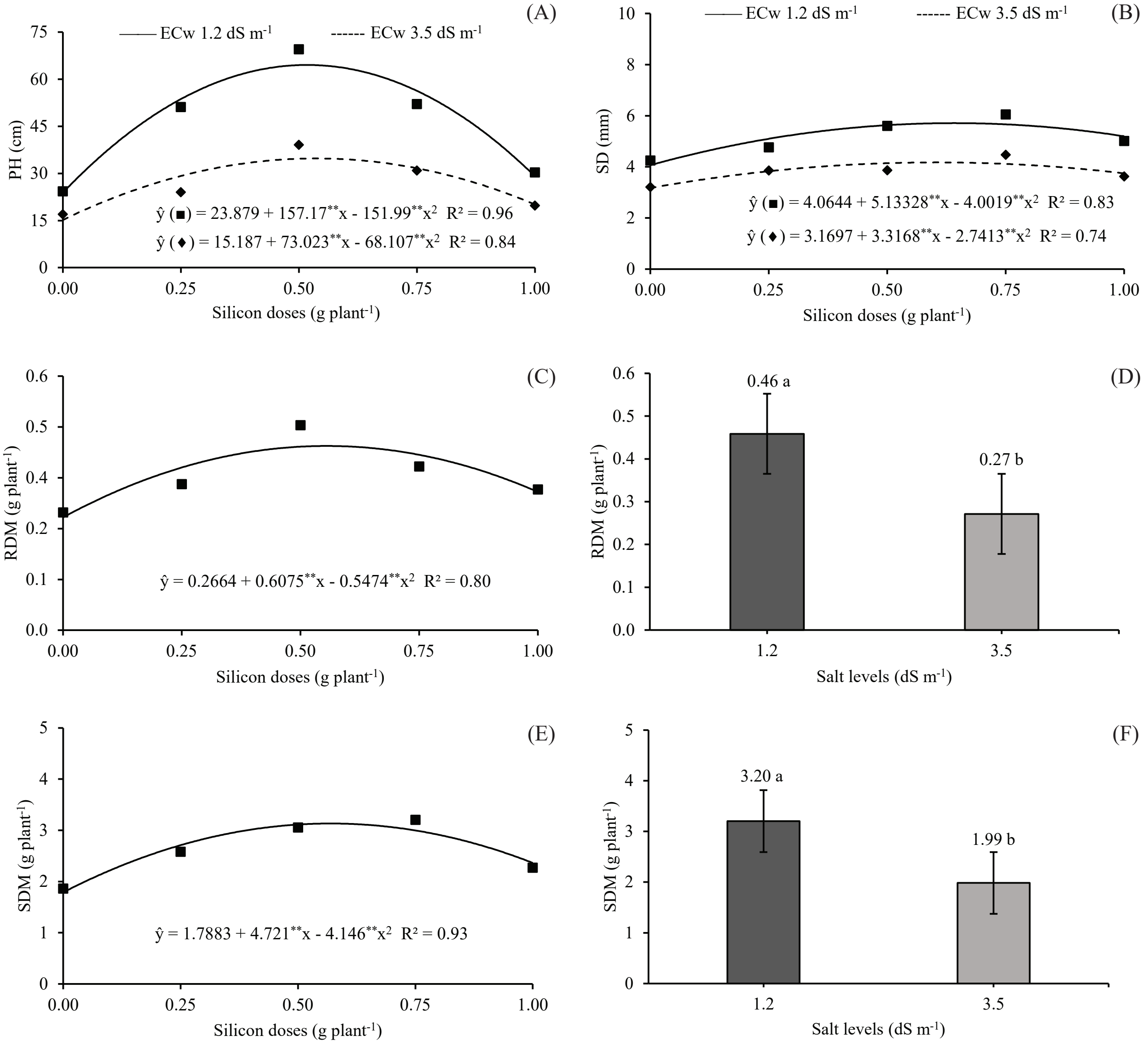


Figure 2. Plant height (PH), stem diameter (SD), shoot dry mass (SDM) and root dry mass (RDM) of yellow passion fruit seedlings subjected to silicate fertilization and saline stress. Different letters indicate statistically significant differences by the F test ($p < 0.05$). ** Significant at $p < 0.01$, according to the linear regression analysis. ECw: electrical conductivity of the water.

Furthermore, when the seedlings were irrigated with water with electrical conductivity of 1.2 dS m^{-1}, they showed a greater dry mass accumulation in the shoot, averaging 3.20 g $plant^{-1}$. In contrast, the seedlings irrigated with 3.5 dS m^{-1} water averaged 1.99 g $plant^{-1}$, representing a reduction of 37.50 %, if compared to the lowest saline level (Figure 2D).

The root dry mass data were significantly affected by the silicon doses, fitting a quadratic regression model (Figure 2E). The highest value (0.43 g $plant^{-1}$) for root dry mass was observed at the dose of 0.55 g $plant^{-1}$ of silicon, corresponding to an increase of 59.25 % in comparison to the root dry mass without silicon application. That may have occurred because silicic acid improves the efficiency of nutrient assimilation in plants, promoting a more robust growth (Figueiredo et al. 2024). It acts as an internal signal that optimizes the plant's response to adverse conditions and improves its development capacity (Ahmed et al. 2021).

The seedlings irrigated with 1.2 dS m^{-1} water showed a higher root dry mass in comparison to those irrigated with 3.5 dS m^{-1} water, with values of 0.46 and 0.27 g, respectively (Figure 2F). This result highlights the negative impact of high salinity on root growth, possibly due to osmotic restriction, toxic effects of ions and nutritional imbalances caused by salt accumulation in the root zone (Liu et al. 2019).

For the relative water content (Figure 3A), a fit to the quadratic model was observed for both plants subjected to the saline levels of 1.2 dS m^{-1} and 3.5 dS m^{-1}. The highest relative water content values (80.45 and 68.95 %) occurred with doses of 0.71 and 0.81 g $plant^{-1}$ of silicon, at salt levels of 1.2 and 3.5 dS m^{-1}, respectively. Plants irrigated with 1.2 dS m^{-1} water were 16.68 % better than those irrigated with 3.5 dS m^{-1} water (Figure 3A). The increase in relative water content can be attributed to the plants' improved osmotic adjustment due to silicon application, which enables a greater water absorption and retention, even under saline stress (Zhu et al. 2019). Silicon may have modulated the water potential, promoting a better water retention in the leaf tissue and mitigating the effects of osmotic stress.

For plants irrigated with 1.2 and 3.5 dS m^{-1} water, the electrolyte leakage fitted quadratic models, with minimum values (19.01 and 30.90 %) occurring at doses of 0.59 and 0.65 g $plant^{-1}$ of silicon, respectively (Figure 3B). These results correspond to 29.14 and 33.98 % reductions in the cell electrolyte leakage, when compared to plants without silicon application. Decreases in electrolyte leakage due to silicon application highlight this element's benefits for strengthening plants, thus contributing to preserving cell membrane integrity (Rastogi et al. 2021).

The silicon doses significantly affected the plants' water-use efficiency, fitting a quadratic model (Figure 3C). The dose of 0.55 g $plant^{-1}$ of silicon provided a greater water-use efficiency, with an increase of 54.93 %, when compared to plants without silicon, demonstrating the beneficial effect of silicic acid for the yellow passion fruit. When irrigated with 1.2 dS m^{-1} water, the seedlings showed a greater water-use efficiency, when compared to those irrigated with 3.5 dS m^{-1} water (Figure 3D).

For the CO_2 assimilation, a quadratic trend was observed in the data as a function of the silicon doses (Figure 4A). When they received doses of 0.51 g of silicon, the plants assimilated more CO_2

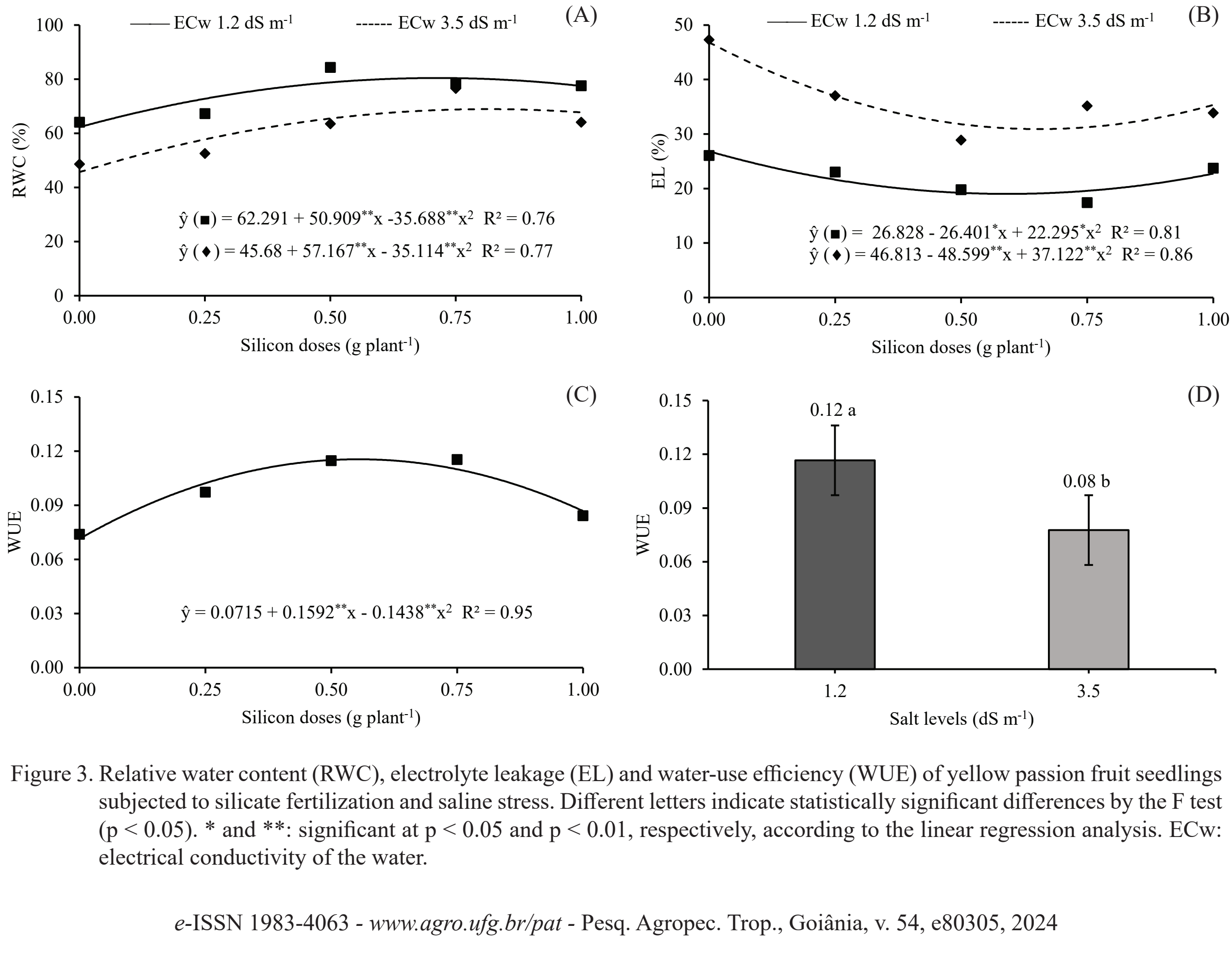


Figure 3. Relative water content (RWC), electrolyte leakage (EL) and water-use efficiency (WUE) of yellow passion fruit seedlings subjected to silicate fertilization and saline stress. Different letters indicate statistically significant differences by the F test ($p < 0.05$). * and **: significant at $p < 0.05$ and $p < 0.01$, respectively, according to the linear regression analysis. ECw: electrical conductivity of the water.

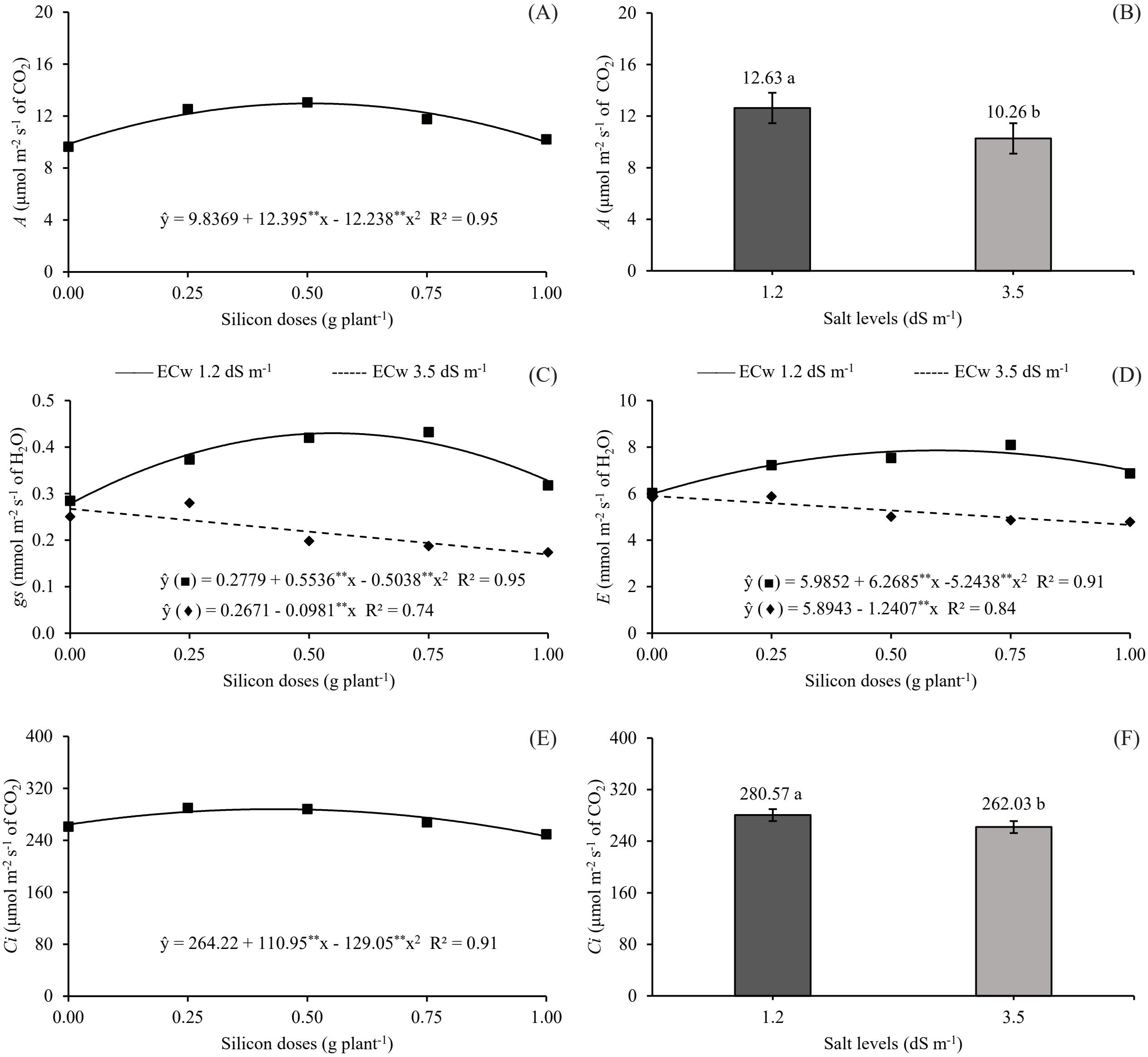


Figure 4. CO_2 assimilation rate (*A*), stomatal conductance (*gs*), transpiration (*E*) and internal CO_2 concentration (*Ci*) for yellow passion fruit seedlings subjected to silicate fertilization and salt stress. Different letters indicate statistically significant differences by the F test ($p < 0.05$). ** Significant at $p < 0.01$, according to the linear regression analysis. ECw: electrical conductivity of the water.

(12.97 μmol m^{-2} s^{-1} of CO_2). When comparing this value with that obtained from the plants that did not receive silicon (9.83 μmol m^{-2} s^{-1} of CO_2), the CO_2 assimilation rate increased 31.94 %. The assimilation of CO_2 of the plants irrigated with 3.5 dS m^{-1} water showed an average of 10.26 μmol m^{-2} s^{-1}. Meanwhile, the CO_2 assimilation rate of the plants irrigated with 1.2 dS m^{-1} water showed an average value of 12.63 μmol m^{-2} s^{-1} of CO_2, reflecting the negative effect of salts on the photosynthesis of passion fruit seedlings (Figure 4B).

Regarding stomatal conductance (Figure 4C), a quadratic behavior was also observed as a function of the silicon doses, when the plants were irrigated with 1.2 dS m^{-1} water, with the highest value (0.42 mmol m^{-2} s^{-1} of CO_2) occurring at the dose of 0.54 g $plant^{-1}$ of silicon. It is worth noting that these results were 60 % better than those of plants without silicon application (0.27 mmol m^{-2} s^{-1} of H_2O). When the plants were irrigated with 3.5 dS m^{-1} water, the stomata conductance showed a decreasing linear trend, as a function of the silicon doses, with a reduction of 0.09 mmol m^{-2} s^{-1} of H_2O for each unit increase in the silicon dose.

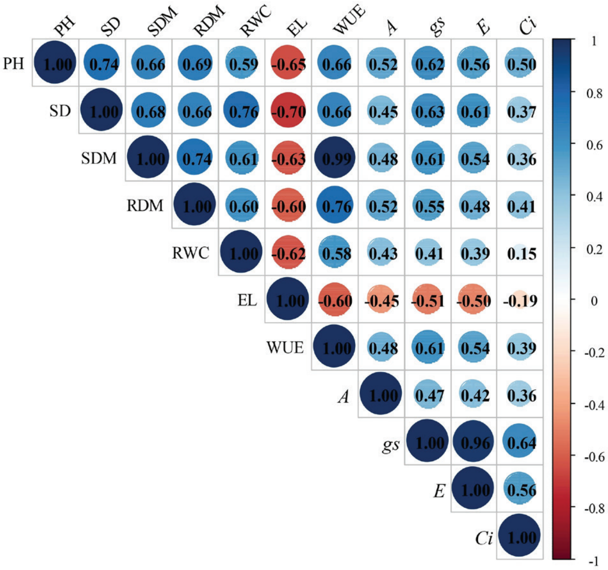
Transpiration showed higher values with the dose of 0.60 g plant^{-1} of silicon in plants irrigated with 1.2 dS m^{-1} water, fitting a quadratic model. When irrigated with 3.5 dS m^{-1} water, a decreasing linear effect occurred, with the value for plant transpiration decreasing by 1.24 mmol m^{-2} s^{-1} of H_2O for each unit increase in the silicon dose (Figure 4D). This behavior can be explained by the reduction in the plants' stomatal opening in response to the increase in silicon doses, as shown in Figure 4C. These physiological adjustments reflect an essential adaptive mechanism to reduce water loss through transpiration, which is highly relevant for cultivation under saline conditions and, above all, in semi-arid regions, where maximum temperatures reach high values, often exceeding 40 ºC (Figure 1).

The internal CO_2 concentration was significantly affected by the silicon doses, with a quadratic behavior of the data (Figure 4E). The highest value (288.06 µmol m^{-2} s^{-1} of CO_2) occurred with a dose of 0.43 g plant^{-1} of silicon. When compared to the non-application of silicon (264.22 µmol m^{-2} s^{-1} of CO_2), the internal carbon concentration showed an increase of 9.02 %. An increase of 7.07 % was observed for the internal CO_2 concentration when the plants were irrigated with 1.2 dS m^{-1} water, if compared to plants irrigated with 3.5 dS m^{-1} water (Figure 4F). This reduction in the internal concentration of CO_2 in plants under salt stress is mainly caused by the closure of the stomata, which limits the assimilation of CO_2 and compromises the photosynthetic process (Lima et al. 2021).

The correlation matrix shown in Figure 5 revealed significant positive correlations between plant growth and physiological processes. Specifically, the plant height and stem diameter variables showed strong positive correlations with the shoot and root dry masses. Furthermore, the physiological aspects evaluated, such as relative water content, water-use efficiency, net photosynthesis, stomatal conductance, transpiration rate and internal carbon concentration, also showed positive correlations with the variables related to plant biomass growth. These results reinforce the interdependence between physiological functions and plant growth.

On the other hand, the growth and physiology variables had negative correlations with electrolyte leakage, what is an indication of damage to the cell membrane, often associated with abiotic stresses such as drought and salinity, which can compromise cell integrity and therefore the physiological function of plants (Demidchik et al. 2014).

These correlations highlight the importance of a balanced physiology in promoting plant growth, where adequate values for relative water content, water-use efficiency, net photosynthesis, stomatal conductance, transpiration rate, internal carbon concentration and electrolyte leakage are essential to promote the yellow passion fruit growth, preventing cell damage and excessive dehydration. Moreover, the results reinforce the need for management strategies that consider the interaction among growth, physiology and stress, since optimizing a single aspect without considering the effects on other interconnected variables may be insufficient to promote a healthy plant growth. These findings can provide a basis for future research to explore the molecular mechanisms underlying these correlations and develop agricultural practices that maximize the growth potential under adverse conditions.



	PH	SD	SDM	RDM	RWC	EL	WUE	*A*	*gs*	*E*	*Ci*
PH	1.00	0.74	0.66	0.69	0.59	-0.65	0.66	0.52	0.62	0.56	0.50
SD		1.00	0.68	0.66	0.76	-0.70	0.66	0.45	0.63	0.61	0.37
SDM			1.00	0.74	0.61	-0.63	0.99	0.48	0.61	0.54	0.36
RDM				1.00	0.60	-0.60	0.76	0.52	0.55	0.48	0.41
RWC					1.00	-0.62	0.58	0.43	0.41	0.39	0.15
EL						1.00	-0.60	-0.45	-0.51	-0.50	-0.19
WUE							1.00	0.48	0.61	0.54	0.39
A								1.00	0.47	0.42	0.36
gs									1.00	0.96	0.64
E										1.00	0.56
Ci											1.00

Figure 5. Pearson's correlation among growth, mass partitioning and physiological aspects of yellow passion fruit seedlings subjected to silicate fertilization and saline stress (n = 5). PH: plant height; SD: stem diameter; SDM: shoot dry mass; RDM: root dry mass; RWC: relative water content; EL: electrolyte leakage; WUE: water-use efficiency; *A*: net photosynthesis; *gs*: stomatal conductance; *E*: transpiration; *Ci*: internal carbon concentration.

CONCLUSIONS

Doses between 0.50 and 0.60 g plant^{-1} of silicon provide better results for the growth, water status and physiology of yellow passion fruit seedlings, both under lower (1.2 dS m^{-1}) and higher (3.5 dS m^{-1}) salinity conditions. These doses help to mitigate salt stress, improving the plants' tolerance to excess of salts and promoting a better vegetative growth.

REFERENCES

AHMED, Z. F.; AL SHAIBANI, F. Y.; KAUR, N.; MAQSOOD, S.; SCHMEDA-HIRSCHMANN, G. Improving fruit quality, bioactive compounds, and storage life of date palm (*Phoenix dactylifera* L., cv. Barhi) using natural elicitors. *Horticulturae*, v. 7, n. 9, e293, 2021.

ALMEIDA, E. V.; NATALE, W.; PRADO, R. D. M.; BARBOSA, J. C. Adubação nitrogenada e potássica no desenvolvimento de mudas de maracujazeiro. *Ciência Rural*, v. 36, n. 4, p. 1138-1142, 2006.

ALVARES, C. A.; STAPE, J. L.; SENTELHAS, P. C.; GONÇALVES, J. L. M.; SPAROVEK, G. Köppen's climate classification map for Brazil. *Meteorologisch*, v. 22, n. 6, p. 711-728, 2013.

CAIRO, P. A. R. *Relações hídricas de plantas*. Vitória da Conquista: Ed. UESB, 1995.

CASSEL, J. L.; GYSI, T.; ROTHER, G. M.; PIMENTA, B. D.; LUDWIG, R. L.; SANTOS, D. B. Benefícios da aplicação de silício em plantas. *Brazilian Journal of Animal and Environmental Research*, v. 4, n. 4, p. 6601-6615, 2021.

COSTA, B. N. S.; COSTA, I. J. S.; DIAS, G. M. G.; ASSIS, F. A.; PIO, L. A. S; SOARES, J. D. R.; PASQUAL, M. Morpho-anatomical and physiological alterations of passion fruit fertilized with silicone. *Pesquisa Agropecuária Brasileira*, v. 53, n. 2, p. 163-171, 2016a.

COSTA, B. N. S.; DIAS, G. D. M. G.; COSTA, I. D. J. S.; ASSIS, F. A. D.; SILVEIRA, F. A. D.; PASQUAL, M. Effects of silicon on the growth and genetic stability of passion fruit. *Acta Scientiarum*: *Agronomy*, v. 38, n. 4, p. 503-511, 2016b.

COSTA, M. V. P.; VÁSQUEZ, M. A. N.; RODRIGUES, L. N.; SANTOS, F. G. B.; NERY, A. R.; SANTOS, S. L. L.; ROCHA, C. T. S. Manejo e produtividade de maracujazeiro amarelo em propriedade rural do município de Caririaçu - CE: um estudo de caso. *Research, Society and Development*, v. 12, n. 1, e3812139255, 2023.

DEMIDCHIK, V.; STRALTSOVA, D.; MEDVEDEV, S. S.; POZHVANOV, G. A.; SOKOLIK, A.; YURIN, V. Stress-induced electrolyte leakage: the role of K$^+$-permeable channels and involvement in programmed cell death and metabolic adjustment. *Journal of Experimental Botany*, v. 65, n. 5, p. 1259-1270, 2014.

DINIZ, G. L.; NOBRE, R. G.; LIMA, G. S.; SOARES, L. A. A.; GHEYI, H. R. Irrigation with saline water and silicate fertilization in the cultivation of 'Gigante Amarelo' passion fruit. *Revista Caatinga*, v. 34, n. 1, p. 199-207, 2021.

DINIZ, G. L.; NOBRE, R. G.; LIMA, G. S.; SOUZA, L. P.; GHEYI, H. R.; MEDEIROS, M. N. V. Physiological indices and growth of 'Gigante Amarelo' passion fruit under salt stress and silicate fertilization. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 24, n. 12, p. 814-821, 2020a.

DINIZ, G. L.; NOBRE, R. G.; LIMA, G. S.; SOUZA, L. P.; SOARES, L. A. A.; GHEYI, H. R. Phytomass and quality of yellow passion fruit seedlings under salt stress and silicon fertilization. *Comunicata Scientiae*, v. 11, e3400, 2020b.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (Embrapa). *Manual de análises químicas de solos, plantas e fertilizantes*. 2. ed. Brasília, DF: Embrapa Informação Tecnológica, 2009.

FIGUEIREDO, G. F. V.; DANTAS, J. S.; MESQUITA, E. F.; PEREIRA, R. F.; MELO, D. R. M.; NOGUEIRA, V. D. F. B.; SOUSA, C. S.; DINIZ, J. P. C. Influence of soil organic matter on okra mineral nutrition and yield. *Pesquisa Agropecuária Tropical*, v. 54, e79784, 2024.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). *Produção agrícola municipal (2023)*. 2024. Available at: https://www.ibge.gov.br/explica/producao-agropecuaria/maracuja/br. Access on: Nov. 28, 2024.

IRFAN, M.; MAQSOOD, M. A.; REHMAN, H.; MAHBOOB, W.; SARWAR, N.; HAFEEZ, O. B. A.; HUSSAIN, S.; ERCISLI, S.; AKHTAR, M.; AZIZ, T. Silicon nutrition in plants under water-deficit conditions: overview and prospects. *Water*, v. 15, n. 4, e739, 2023.

JESUS, E. G.; FÁTIMA, R. T.; GUERRERO, A. C.; ARAÚJO, J. L.; BRITO, M. E. B. Crescimento e trocas gasosas de plantas de rúcula sob adubação silicatada e restrição hídrica. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 2, n. 2, p. 119-124, 2018.

LIMA, G. S. D.; SOARES, M. G. D. S.; SOARES, L. A. D. A.; GHEYI, H. R.; PINHEIRO, F. W.; SILVA, J. B. D. Potassium and irrigation water salinity on the formation of sour passion fruit seedlings. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 25, n. 6, p. 393-401, 2021.

LIMA, G. S. D.; SOUZA, W. B. D.; PAIVA, F. J. D. S.; SOARES, L. A. D. A.; TORRES, R. A.; SILVA, S. T. D. A.; GHEYI, H. R.; LOPES, K. P. Tolerance of sour passion fruit cultivars to salt stress in a semi-arid region. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 27, n. 10, p. 785-794, 2023.

LIU, B.; SOUNDARARAJAN, P.; MANIVANNAN, A. Mechanisms of silicon-mediated amelioration of salt stress in plants. *Plants*, v. 8, n. 9, e307, 2019.

MANDLIK, R.; THAKRAL, V.; RATURI, G.; SHINDE, S.; NIKOLIĆ, M.; TRIPATHI, D. K.; SONAH, H.; DESHMUKH, R. Significance of silicon uptake, transport, and deposition in plants. *Journal of Experimental Botany*, v. 71, n. 21, p. 6703-6718, 2020.

MELO, A. R.; BEZERRA, A. C.; LIMA JÚNIOR, A. R.; SILVA, M. B. P.; SILVA, E. A.; LEÃO, A. C.; ANDRADE, L. F. S.; ZUZA, J. F. C. Produção de mudas de maracujazeiro amarelo com diferentes concentrações de esterco bovino no substrato. *Brazilian Journal of Animal Environmental Research*, v. 2, n. 4, p. 1323-1330, 2019.

MESQUITA, E. F.; MESQUITA, F. O.; SOUSA, C. S.; COSTA, J. P.; DINIZ, L. L. G. D. Q.; SOARES, V. C. S.; TARGINO, F. N.; JALES, D. V. D.; BRITO NETO, J. F.; ROCHA, J. L. A.; SOUTO, A. G. L. Silício e adubação orgânica sobre os atributos físico-químicos de frutos de maracujá-amarelo no semiárido Brasil. *Revista Brasileira de Geografia Física*, v. 17, n. 1, p. 100-116, 2024.

NASCIMENTO, E. S.; CAVALCANTE, L. F.; GONDIM, S. C.; SOUZA, J. T. A.; BEZERRA, F. T. C.; BEZERRA, M. A. F. Formação de mudas de maracujazeiro amarelo irrigadas com águas salinas e biofertilizantes de esterco bovino. *Revista Agropecuária Técnica*, v. 38, n. 1, p. 1-8, 2017.

R CORE TEAM. *R*: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2023.

RASTOGI, A.; YADAV, S.; HUSSAIN, S.; KATARIA, S.; HAJIHASHEMI, S.; KUMARI, P.; YANG, X.; BRESTIC, M. Does silicon really matter for the photosynthetic machinery in plants…? *Plant Physiology and Biochemistry*, v. 169, n. 1, p. 40-48, 2021.

RIOS, J. J.; MARTÍNEZ-BALLESTA, M. C.; RUIZ, J. M.; BLASCO, B.; CARVAJAL, M. Silicon-mediated improvement in plant salinity tolerance: the role of aquaporins. *Frontiers in Plant Science*, v. 8, e948, 2017.

SÁ, J. R.; TOLEDO, F. H. S. F.; MARIÑO, Y. A.; SOARES, C. R. F. S.; FERREIRA, E. V. O. Growth and nutrition of *Passiflora edulis* submitted to saline stress after silicon application. *Revista Brasileira de Fruticultura*, v. 43, n. 1, e057, 2021.

SCOTTI, C. P.; THI, A. T. P. Effect of abscisic acid pretreatment on membrane leakage and lipid composition of *Vigna unguiculata* leaf discs subject to osmotic stress. *Plant Science*, v. 130, n. 1, p. 11-18, 1997.

SILVA, A. A.; VELOSO, L. L.; LIMA, G. S. D.; AZEVEDO, C. A.; GHEYI, H. R.; FERNANDES, P. D. Hydrogen peroxide in the acclimation of yellow passion fruit seedlings to salt stress. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 25, n. 2, p. 116-123, 2021.

SINGH, P.; KUMAR, V.; SHARMA, A. Interaction of silicon with cell wall components in plants: a review. *Journal of Applied and Natural Science*, v. 15, n. 2, p. 480-497, 2023.

WEYYA, G.; BELAY, A.; TADESSE, E. Passion fruit (*Passiflora edulis* Sims) by-products as a source of bioactive compounds for non-communicable disease prevention: extraction methods and mechanisms of action: a systematic review. *Frontiers in Nutrition*, v. 11, e1340511, 2024.

ZHU, Y.-X.; GONG, H.-J.; YIN, J.-L. Role of silicon in mediating salt tolerance in plants: a review. *Plants*, v. 8, n. 6, e147, 2019.