

Gas exchange, photochemical efficiency, and production of okra under saline water irrigation and potassium fertilization

Trocas gasosas, eficiência fotoquímica e produção de quiabeiro irrigado com águas salinas e adubação potássica

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ABSTRACT - Water scarcity has intensified the use of saline water in irrigated agriculture, compromising the physiological performance and production of crops, particularly okra. Among management strategies, potassium fertilization has stood out as a promising alternative in mitigating the effects of salt stress on plants. The objective was to evaluate the influence of potassium fertilization on gas exchange, chlorophyll *a* fluorescence, and production components of okra under irrigation with saline water. The experiment was conducted in a randomized block design in a 5×5 factorial arrangement, with five irrigation water salinity levels ($EC_w = 0.3, 1.3, 2.3, 3.3, \text{ and } 4.3 \text{ dS m}^{-1}$) and five potassium doses (50, 75, 100, 125, and 150% of the recommended K_2O dose), with 100% corresponding to $150 \text{ mg K}_2\text{O kg}^{-1}$ of soil, with three replications. Gas exchange, chlorophyll *a* fluorescence, and production components of okra were evaluated. Salinity levels above 0.3 dS m^{-1} reduced the quantum efficiency of photosystem II, fruit length, and fresh fruit weight of okra cv. Santa Cruz. Fertilization with 150% of the recommended K_2O dose decreased stomatal conductance, transpiration, and the CO_2 assimilation rate of okra irrigated with water of 4.3 dS m^{-1} . Under semi-arid edaphoclimatic conditions, fertilization with 150% K_2O mitigated the effects of salt stress on the fruit diameter of okra irrigated under an EC_w of 4.3 dS m^{-1} .

RESUMO - A escassez hídrica tem intensificado o uso de águas salinas na agricultura irrigada, comprometendo o desempenho fisiológico e a produção das culturas, particularmente do quiabeiro. Dentre as estratégias de manejo, a adubação potássica tem se destacado como alternativa promissora na mitigação dos efeitos do estresse salino nas plantas. Objetivou-se avaliar a influência da adubação potássica nas trocas gasosas, na fluorescência da clorofila *a* e nos componentes de produção do quiabeiro sob irrigação com águas salinas. O experimento foi conduzido em delineamento em blocos casualizados em arranjo fatorial 5×5 , com cinco níveis de salinidade da água de irrigação ($CEa = 0,3, 1,3, 2,3, 3,3 \text{ e } 4,3 \text{ dS m}^{-1}$) e cinco doses de potássio (50, 75, 100, 125 e 150% da dose recomendada de K_2O), com 100% correspondendo a $150 \text{ mg de K}_2\text{O kg}^{-1}$ de solo, com três repetições. Foram avaliadas as trocas gasosas, a fluorescência da clorofila *a* e os componentes de produção do quiabeiro. Níveis de salinidade acima de $0,3 \text{ dS m}^{-1}$ reduziu a eficiência quântica do fotossistema II, o comprimento e a massa fresca dos frutos de quiabeiro cv. Santa Cruz. A adubação com 150% da recomendação de K_2O diminuiu a condutância estomática, a transpiração e a taxa de assimilação de CO_2 do quiabeiro irrigado com água de $4,3 \text{ dS m}^{-1}$. Nas condições edafoclimáticas de semiárido, a adubação com 150% de K_2O amenizou os efeitos do estresse salino no diâmetro dos frutos do quiabeiro irrigado sob CEa de $4,3 \text{ dS m}^{-1}$.

Keywords: *Abelmoschus esculentus* L.. Salt stress. Osmoregulation.

Palavras-chave: *Abelmoschus esculentus* L.. Estresse salino. Osmorregulação.

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INTRODUCTION

Belonging to the Malvaceae family, okra (*Abelmoschus esculentus* L.) is a vegetable adapted to tropical and subtropical climates and is cultivated in Brazil mainly by small producers due to its high nutritional value, hardiness, fast growth cycle, and high profitability. (SANTOS et al., 2019). Its fruit is rich in carbohydrates, proteins, fatty acids, vitamins, fiber, and minerals, as well as various bioactive phytochemicals essential for human well-being. Due to its high nutritional value, okra has the potential to mitigate malnutrition in developing countries worldwide (ELKHALIFA et al., 2021).

In the arid and semiarid regions of Brazil, irrigation is essential for agricultural production. However, farmers often rely on low-quality water sources with high salinity levels, which can reduce okra yield (PINHEIRO et al., 2023). In this scenario, excessive salt accumulation in the soil poses environmental risks, e.g., soil salinization and sodification, threatening natural resources in the Brazilian semiarid region (SILVA et al., 2021). These conditions impair plant growth and development by disrupting physiological processes, including ionic balance, mineral nutrition, stomatal behavior, and photosynthetic efficiency (NAJAFI; REZAEI; MOZAFARIAN, 2024). Okra is classified as sensitive to salt

stress, with the threshold salinity level for irrigation water being 1.3 dS m^{-1} (UPADHYAY; SINGH; CHAUBEY, 2020). Under salt stress conditions, okra typically experiences inhibited growth (LIMA et al., 2020a), impaired synthesis of photosynthetic pigments, alterations in gas exchange (SALES et al., 2023), and a reduction in production components (LIMA et al., 2020b; MENDONÇA et al., 2022). However, the level of plant tolerance can vary depending on the cultivar, stage of development, soil and climate conditions, irrigation and fertilization practices, and water quality (LIMA et al., 2022; PINHEIRO et al., 2023).

Among the strategies to mitigate salt stress, potassium fertilization stands out as a viable approach (LIMA et al., 2022; SALES et al., 2023; PINHEIRO et al., 2023). Potassium can alleviate salinity-induced damage by enhancing reactive oxygen species (ROS) scavenging under osmotic stress, strengthening antioxidant enzyme activity, and improving nitrogen use efficiency, thereby sustaining crop yields under stress conditions (KUMARI et al., 2023). Moreover, this macronutrient regulates stomatal opening and closure, activates key enzymes involved in photosynthesis and respiration, and maintains guard cell turgor (SALES et al., 2023). The induction of plant tolerance to salt stress mediated by K^+ is related to increased levels of antioxidant enzymes and reduced lipid peroxidation of membranes mediated by oxidative stress (PRAVEEN; SINGH, 2024).

However, studies exploring the benefits of potassium fertilization combined with saline water management in okra cultivation under semiarid conditions remain scarce. Potassium contributes to the antioxidant system and reduces

the cytosolic Na^+/K^+ ratio, restoring ionic and nutritional homeostasis (TITTAL et al., 2021). Sales et al. (2023) investigated the combined effects of nitrogen and potassium fertilization on salt stress mitigation in okra and found that a fertilization regime of 40% N + 40% K_2O reduced salt-induced damage and increased the chlorophyll content. The hypothesis of this study is that potassium fertilization increases osmoregulation capacity, contributing to plant tolerance to salt stress by maintaining Na^+/K^+ homeostasis and increasing photosynthetic efficiency through the regulation of stomatal dynamics. However, such studies evaluated combined nutrient regimes, leaving uncertain the isolated effect of potassium on okra physiology under salinity. Therefore, this study aimed to evaluate the effects of potassium fertilization on gas exchange, chlorophyll *a* fluorescence, and production components of okra under different irrigation water salinity levels.

MATERIAL AND METHODS

The study was conducted between August 1st and November 21st, 2018, under greenhouse conditions at the Center for Science and Agri-Food Technology (CCTA) of the Federal University of Campina Grande (UFCG), located in Pombal, Paraíba, Brazil ($6^\circ 47' 20'' \text{ S}$, $37^\circ 48' 01'' \text{ W}$, elevation above sea level: 194 m). Meteorological data were collected during the experiment using a portable digital thermohygrometer and are presented in Figure 1.

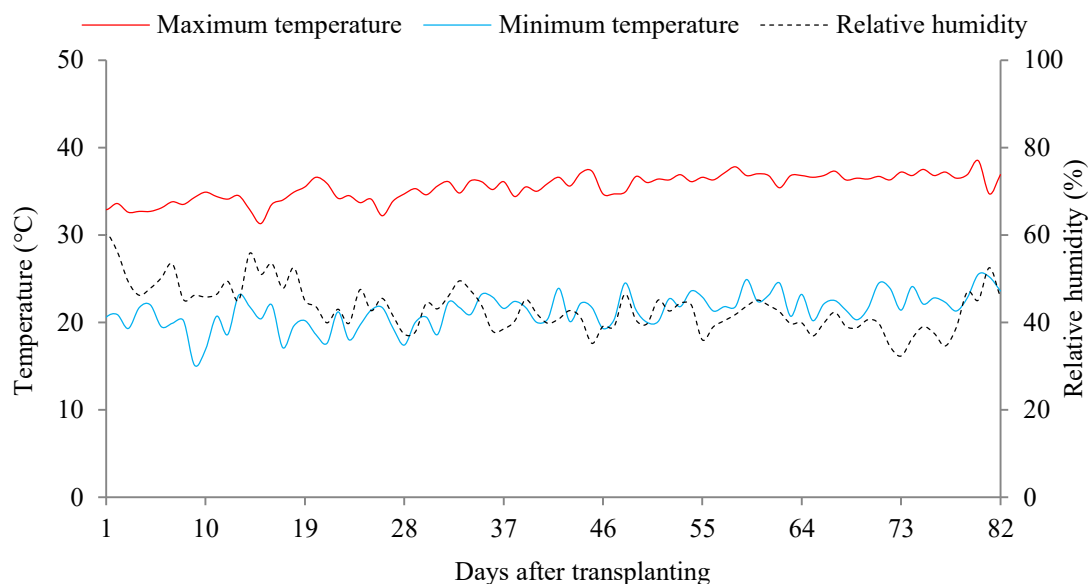


Figure 1. Maximum and minimum temperature and relative humidity data collected between August 1st and November 21st, 2018.

The experiment followed a randomized block design in a 5×5 factorial arrangement, consisting of five levels of irrigation water electrical conductivity (EC_w) (0.3, 1.3, 2.3, 3.3, and 4.3 dS m^{-1}) and five potassium fertilization levels (50, 75, 100, 125, and 150% of the recommended K_2O dose for pot trials, according to Novais, Neves and Barros (1991). The combination of these factors resulted in 25 treatments,

with three replicates and one plant per experimental unit, totaling 75 experimental units. Although the number of replicates was limited to three, this experimental design has been widely adopted in controlled physiological studies due to the high experimental control and reduced variability within the treatment.

Okra plants (*Abelmoschus esculentus* L.), cv. Santa

Cruz, were cultivated in plastic containers adapted as drainage lysimeters (20 L capacity; 35 cm height × 31 cm upper diameter × 20 cm lower diameter) and arranged with a spacing of 1.0 m between rows and 0.6 m between plants. To prevent drainage obstruction, the end of the drainage tube inside each lysimeter was wrapped with a geotextile membrane and covered with a 3 cm layer of gravel.

Below each drainage outlet, 2-L PET bottles were

placed to collect drained water and estimate plant water consumption. The containers were then filled with 24.5 kg of *Neossolo Regolítico eutrófico* (Psamment), classified as sandy loam (collected from a 0–20 cm depth). The soil was previously crushed to break up aggregates, sieved, and characterized for its chemical and physical-hydraulic properties (Table 1), following the methodology of Teixeira et al. (2017).

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

Chemical characteristics								
pH H ₂ O (1:2.5)	OM (g kg ⁻¹)	P (mg kg ⁻¹)	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	H ⁺
cmolc kg ⁻¹								
5.58	2.93	39.2	0.23	1.64	9.07	2.78	0.0	8.61
Chemical characteristics				Physical characteristics				
EC _{se} (dS m ⁻¹)	CEC (cmolc kg ⁻¹)	SAR (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
2.15	22.33	0.67	7.34	572.7	100.7	326.6	25.91	12.96

pH – hydrogen potential; OM – Organic matter; P – Phosphorus; K⁺ – Potassium; Na⁺ – Sodium; Ca²⁺ – Calcium; Mg²⁺ – Magnesium; Al³⁺ – Aluminum; H⁺ – Hydrogen; OM: Walkley-Black Wet Digestion; Ca²⁺ and Mg²⁺ extracted with 1 M KCl at pH 7.0; N⁺ and K⁺ extracted with 1 M NH₄OAc at pH 7.0; Al³⁺ + H⁺ extracted with CaOAc 0.5 M at pH 7.0; EC_{se} – electrical conductivity of the saturation extract; CEC – cation exchange capacity; SAR – sodium adsorption ratio of the saturation extract; ESP – exchangeable sodium percentage; ¹field capacity; ²permanent wilting point.

Sowing was performed using five seeds of the Santa Cruz cultivar per lysimeter at a depth of 3 cm. Soil moisture was maintained at field capacity (25.91 dag kg⁻¹) across all experimental units, using low-salinity water (0.3 dS m⁻¹) until the emergence of the first true leaf, at which point the treatments were initiated. Thinning was conducted at 30 days after sowing (DAS), leaving only one plant per lysimeter.

Nitrogen and phosphorus topdressing was performed according to the fertilization recommendations for pot trials outlined by Novais, Neves and Barros (1991), by applying 100 and 300 mg kg⁻¹ of dry soil of nitrogen and phosphorus, respectively, in the forms of urea and monoammonium phosphate (MAP). These nutrients were applied via irrigation water at 20, 30, and 40 DAS. Potassium fertilization, according to the treatments, was split into four applications via fertigation performed at 10-day intervals starting at 20 DAS. In the K₃ treatment (100% dose, equivalent to 150 mg K₂O kg⁻¹ soil), potassium was supplied as potassium chloride, with the fertilizer quantities for other treatments adjusted accordingly. Micronutrients were supplied biweekly, starting at 20 DAS, using 2.0 g L⁻¹ of the commercial product Micro Rexene®, which contains Mg (1.2%), B (0.85%), Zn (4.2%), Fe (3.4%), Mn (3.2%), Cu (0.5%), and Mo (0.06%).

Low-electrical-conductivity water (0.3 dS m⁻¹) was obtained from the public water supply system of Pombal, PB. The higher-salinity irrigation waters were prepared to achieve a Na:Ca:Mg ratio of 7:2:1, following the relationship between water electrical conductivity and salt concentration described by Richards (1954), as per Equation 1:

$$C \text{ (mmolc L}^{-1}\text{)} = 10 \times \text{ECw} \quad (1)$$

where:

C = salt concentration to be applied (mmolc L⁻¹); and, ECw = electrical conductivity of water (dS m⁻¹)

ECw levels were monitored before each irrigation event. Prior to sowing, soil moisture was raised to its maximum water retention capacity. Irrigation was performed daily using low-electrical-conductivity water (0.3 dS m⁻¹) until the emergence of the first fully developed leaf (17 DAS), at which point treatments with different salinity levels began. The irrigation volume was determined based on the water balance method, replacing the plants' average daily water consumption, with a leaching fraction applied uniformly across all treatments every 15 days. The applied volume (mL) was divided by 0.9 to achieve a 10% leaching fraction, ensuring salt removal from the root zone, as per Equation 2:

$$\text{VC} = \frac{\text{VA} - \text{VD}}{1 - \text{LF}} \quad (2)$$

where:

VC – volume consumed (L),

VA – volume of water applied on the previous day;

VD – volume drained, quantified the following morning; and LF – leaching fraction

Weed control was performed manually to prevent interspecific competition for water and nutrients. Pest management included the application of chemical pesticides via manual backpack sprayers, with insecticide treatments for whiteflies and aphids.

Gas exchange measurements were conducted at 53 DAS, including stomatal conductance (g_s, mol H₂O m⁻² s⁻¹),

transpiration rate (E , $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), net CO_2 assimilation rate (A , $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), and internal CO_2 concentration (C_i , $\mu\text{mol mol}^{-1}$). Based on these measurements, the instantaneous water use efficiency ($IWUE$, A/E) [$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$] ($\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) $^{-1}$] and the instantaneous carboxylation efficiency (ICE , A/C_i) [$(\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}) (\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1})^{-1}$] were estimated. Measurements were taken using an infrared gas analyzer (IRGA) (LCpro+ Portable Photosynthesis System®, ADC Bioscientific, UK) between 7:00 and 10:00 am, using a fully expanded leaf, counted from the apical meristem, under natural temperature and CO_2 concentration, with an artificial radiation source of $1200 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$.

At this same time (53 DAS), chlorophyll a fluorescence was also evaluated through initial fluorescence (F_0), maximum fluorescence (F_m), variable fluorescence (F_v), and quantum efficiency of photosystem II (F_v/F_m) in leaves pre-adapted to darkness using leaf clips for 30 minutes, between 7:00 and 10:00 am, on the middle leaf of the intermediate productive branch of the plant in order to ensure that all the first acceptors were oxidized, i.e., the reaction centers were open.

Fruit harvesting was performed manually between 59 and 82 DAS, based on the characteristic green color indicative

of maturity, totaling 14 harvests. The data presented in this work refers to the average per plant. The fresh fruit weight (FW) of the harvested fruits was recorded using a precision balance (0.01 g). The average fruit length (FL) was determined by measuring the distance from the fruit tip to the peduncle insertion point using a graduated ruler (cm), while the average fruit diameter (FD) was measured with a digital caliper (mm).

Data were subjected to normality testing (Shapiro-Wilk), followed by analysis of variance (ANOVA) at a 0.05 probability level. When significant differences were detected, polynomial regression analysis was applied using the SISVAR – ESAL, version 5.7 statistical software.

RESULTS AND DISCUSSION

The interaction between the levels of electrical conductivity of the water and potassium doses significantly influenced (Table 2) the stomatal conductance (g_s), transpiration (E), internal CO_2 concentration (C_i), CO_2 assimilation rate (A), instantaneous water use efficiency ($IWUE$) and intrinsic carboxylation efficiency (ICE) of okra cv. Santa Cruz, 53 days after sowing.

Table 2. Summary of the analysis of variance for stomatal conductance (g_s), transpiration (E), internal CO_2 concentration (C_i), CO_2 assimilation rate (A), instantaneous water use efficiency ($IWUE$), and intrinsic carboxylation efficiency (ICE) of okra cv. Santa Cruz cultivated under irrigation water salinity and potassium doses.

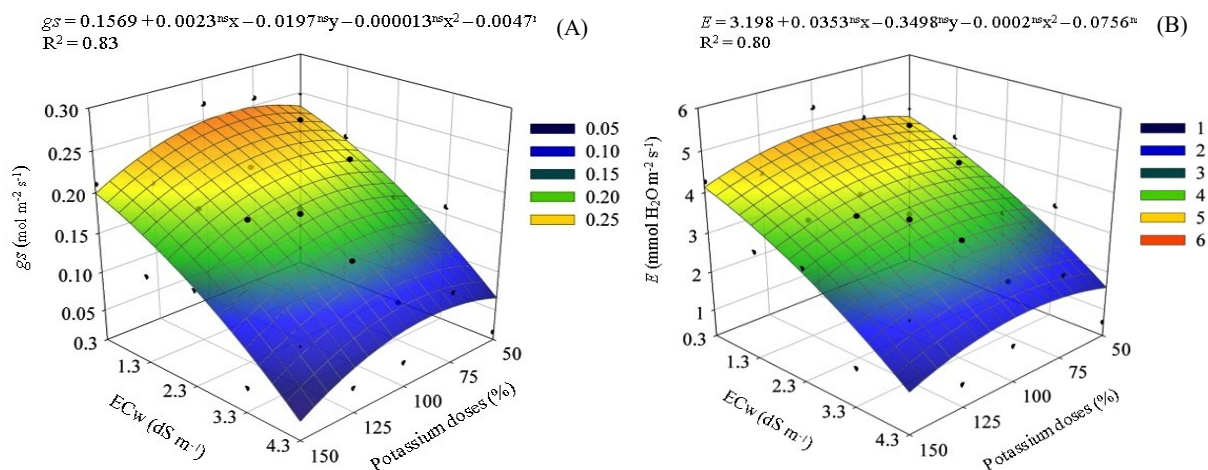
Source of variation	DF	Mean squares					
		g_s	E	C_i	A	$IWUE$	ICE
Salinity levels (SL)	4	0.064**	18.92**	24732.84**	504.81**	17.13**	0.017**
Linear regression	1	0.25**	73.02**	67713.12**	1782.96**	37.35**	0.05**
Quadratic regression	1	0.004*	1.20 ^{ns}	23574.40**	196.71**	21.30**	0.009**
Doses of potassium (DK)	4	0.006*	1.09*	2048.51*	19.04*	3.19*	0.0008*
Linear regression	1	0.01*	0.58 ^{ns}	1050.72 ^{ns}	16.43 ^{ns}	3.90*	0.0000 ^{ns}
Quadratic regression	1	0.01*	2.92*	3934.67*	30.10*	1.39 ^{ns}	0.0001 ^{ns}
Interaction (SL × DK)	16	0.007**	2.56**	8445.05**	79.11**	4.35**	0.003**
Blocks	2	0.0002 ^{ns}	0.72 ^{ns}	24.65 ^{ns}	0.32 ^{ns}	2.46 ^{ns}	0.000001 ^{ns}
Residual	48	0.001	0.34	549.51	6.10	0.47	0.0002
CV		21.09	18.08	10.97	19.14	18.86	23.52

DF - degrees of freedom; CV (%) - coefficient of variation; * - significant at 0.05 probability level; ** - significant at 0.01 probability level; ^{ns} - not significant.

Stomatal conductance (g_s) increased from 0.23 to $0.25 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ as potassium fertilization increased from 50% to 88% of K_2O at an electrical conductivity (ECw) of 0.3 dS m^{-1} . However, further increases in potassium dose and salinity levels resulted in a decline in g_s , with the lowest values observed at ECw 4.3 dS m^{-1} and 150% K_2O , reaching $0.03 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ (Figure 2A). The initial increase in stomatal conductance up to 88% K_2O can be attributed to the role of potassium in maintaining leaf osmotic balance, which enhances cell turgor and promotes stomatal opening (LIMA et al., 2022). However, the rise in ECw led to a reduction in g_s , a response directly associated with plant mechanisms for coping with salt stress. Salt accumulation in the rhizosphere reduces the osmotic potential, thereby limiting water absorption and

inducing stomatal closure (LIMA et al., 2020b).

Maximum transpiration ($4.64 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) was observed in plants irrigated with an ECw of 0.3 dS m^{-1} and fertilized with 88% K_2O , whereas a 76.50% reduction was recorded in plants under an ECw of 4.3 dS m^{-1} and 150% K_2O compared to the maximum value (Figure 2B). The reduction in transpiration is primarily associated with diffusion limitation imposed by stomatal closure, common in plants grown under salt stress conditions (MENDONÇA et al., 2022). According to Lima et al. (2020a), stomatal regulation plays a crucial role in transpiration demand, as plants under salt stress increase stomatal resistance to water vapor flux, reducing excessive water loss.

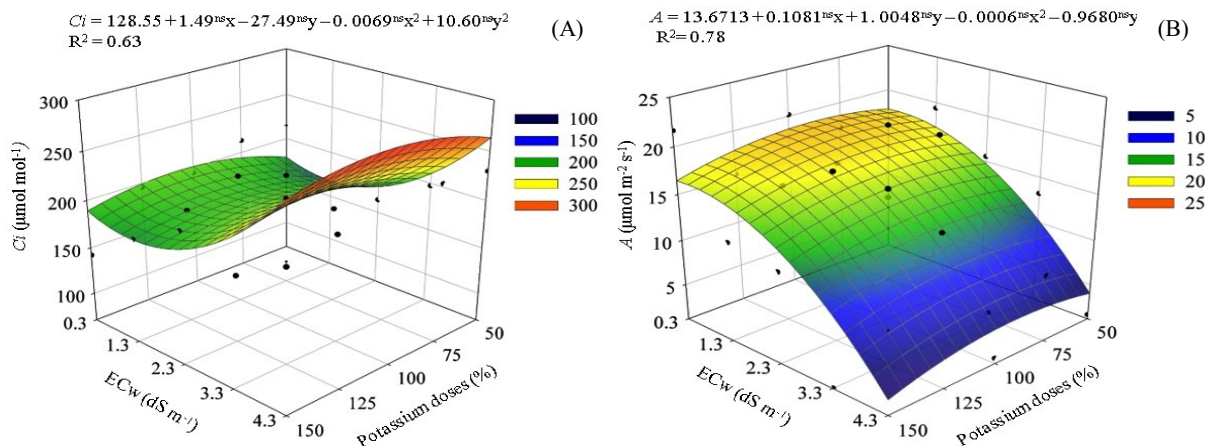


X and Y correspond to the potassium doses and electrical conductivity of irrigation water, respectively. ^{ns}, not significant at $p > 0.05$ by the F-test

Figure 2. Stomatal conductance - g_s (A), and transpiration rate - E (B) in okra cv. Santa Cruz, as a function of the interaction between salinity levels of irrigation water (ECw) and potassium doses.

The internal CO_2 concentration (C_i) increased with rising potassium doses and ECw, reaching a maximum estimated value of $286.77 \mu\text{mol mol}^{-1}$ at 108% K_2O and ECw of 4.3 dS m^{-1} . Conversely, the lowest C_i values ($167.97 \mu\text{mol mol}^{-1}$) were observed in plants treated with 50% K_2O and ECw of 1.3 dS m^{-1} (Figure 3A). The increase in C_i due to excess salts in irrigation water and fertilizer application suggests biochemical limitation of photosynthesis resulting

from phytotoxic damage caused by ion accumulation, leading to reduced RuBisCO activity and possibly lower carbon assimilation in the Calvin cycle (PAN et al., 2021). Thus, the accumulation of CO_2 in the substomatal chamber in okra plants may be associated with reduced carboxylation, a fact that did not reflect an increase in the CO_2 assimilation rate (Figure 3B).



X and Y correspond to potassium doses and the electrical conductivity of irrigation water, respectively. ^{ns}, not significant at $p > 0.05$ by the F-test

Figure 3. Internal CO_2 concentration - C_i (A) and CO_2 assimilation rate - A (B) in okra cv. Santa Cruz as a function of the interaction between salinity levels and potassium doses.

The highest CO_2 assimilation rate ($18.80 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) was recorded in plants irrigated with ECw of 0.5 dS m^{-1} and fertilized with 90% of the recommended K_2O dose (Figure 3B). However, increasing salinity levels led to a reduction in A , with the lowest value ($2.80 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) observed at ECw of 4.3 dS m^{-1} under 150% K_2O fertilization, corresponding to an 85.06% decline relative to the highest value. The reduction in A induced by salinity is associated with a sharp drop in g_s and, consequently, in E , highlighting the influence of stomatal opening and closing on gas exchange in plants exposed to irrigation with high salinity (PINHEIRO et al., 2022a). Similarly, excessive K_2O application can have phytotoxic

effects, while insufficient doses fail to provide the necessary supply for maintaining CO_2 assimilation (WANG et al., 2020). Sales et al. (2023) reported similar findings in okra, demonstrating that increasing ECw from 0.3 to 3.1 dS m^{-1} led to linear reductions in E (by $0.48 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ or 13.09%) and A (by $2.66 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ or 21.49%) per unit increase in ECw.

Okra plants irrigated with ECw of 1.5 dS m^{-1} and fertilized with 50% of the recommended K_2O dose exhibited a 10.65% increase in intrinsic water-use efficiency (WUE_i) compared to plants under the same K_2O dose at ECw of 0.3 dS m^{-1} (Figure 4A). The lowest WUE_i values were recorded in plants treated with 150% K_2O under ECw of

4.3 dS m⁻¹. *IWUE*, defined as the ratio of *A* to *g_s*, indicates the carbon assimilation efficiency relative to water loss through transpiration. The observed increase in *IWUE* may be associated with a proportionally greater reduction in *g_s* than in *A*, which maintained the balance between carbon fixation and

water loss. However, excessive salinity and potassium fertilization led to imbalances, reducing carbon fixation and stomatal conductance (*g_s*), thus decreasing *IWUE* (PINHEIRO et al., 2022b).

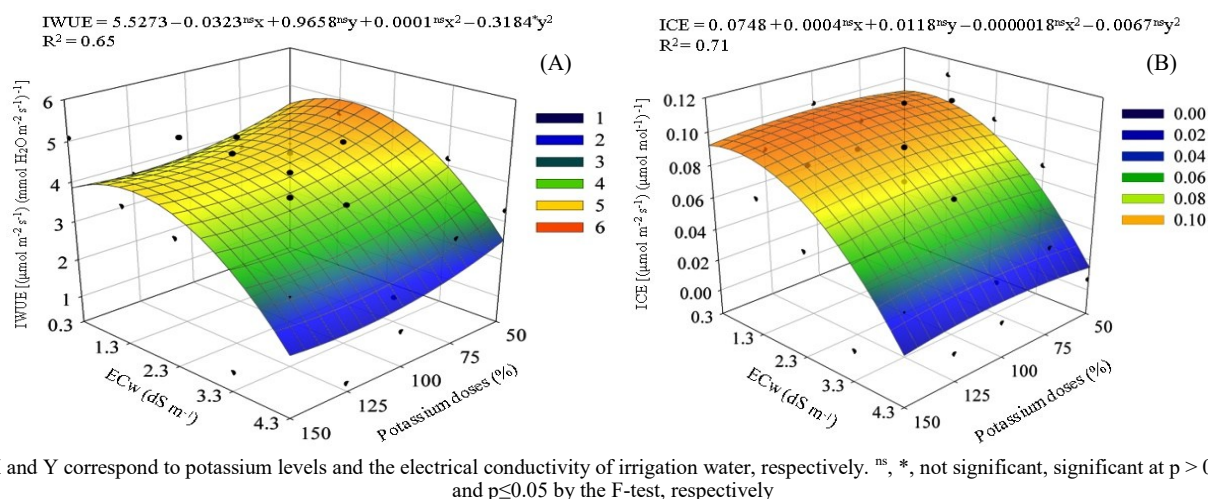


Figure 4. Instantaneous water-use efficiency - *IWUE* (A) and intrinsic carboxylation efficiency - *ICE* (B) in okra cv. Santa Cruz as a function of the interaction between salinity levels and potassium doses.

Instantaneous carboxylation efficiency (*ICE*) reached its highest value (0.09 [(μmol CO₂ m⁻² s⁻¹) (μmol mol⁻¹)⁻¹]) in plants treated with 111% of the recommended K₂O dose and irrigated with an ECw of 0.3 dS m⁻¹. In contrast, the lowest *ICE* was recorded in plants fertilized with 50% K₂O under ECw of 4.3 dS m⁻¹ (Figure 4B). The reduction in *ICE* under high salinity suggests that non-stomatal factors also contributed to photosynthetic inhibition, particularly the decline in Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) activity. This reduction may be attributed to limited availability of essential substrates such as ATP and NADPH, which are required for enzymatic activation and regeneration. Furthermore, potassium plays a critical role in

regulating RuBisCO function, influencing its biosynthesis, nutrient uptake, and water-gas influx to chloroplasts (MASTOFA et al., 2022). Thus, K₂O deficiency also contributes to decreased *ICE*.

There was a significant interaction effect between water electrical conductivity levels and potassium doses (SL × DK) on okra fruit diameter (Table 3). Water salinity levels significantly affected initial fluorescence (*F₀*), photosystem II quantum efficiency (*F_v/F_m*), fruit length (FL), and fresh fruit weight (FW). Potassium doses did not significantly influence any of the measured variables. Regarding maximum (*F_m*) and variable (*F_v*) fluorescence, no significant effect of the evaluated variation sources was observed.

Table 3. Summary of the analysis of variance for fluorescence (*F₀*), maximum fluorescence (*F_m*), variable fluorescence (*F_v*), and the quantum efficiency of photosystem II (*F_v/F_m*), fruit length (FL), fresh fruit weight (FW) and fruit diameter (FD) of okra cv. Santa Cruz cultivated under irrigation water salinity and potassium doses.

Source of variation	DF	Mean squares						
		<i>F₀</i>	<i>F_m</i>	<i>F_v</i>	<i>F_v/F_m</i>	FL	FW	FD
Salinity levels (SL)	4	39088.68*	230447.04 ^{ns}	305608.42 ^{ns}	0.014*	23.02**	6030.38*	6.75**
Linear regression	1	110432.66**	32472.32 ^{ns}	262671.52 ^{ns}	0.031*	84.03**	16809.50*	24.08**
Quadratic regression	1	39059.50**	143890.51 ^{ns}	332887.24 ^{ns}	0.020 ^{ns}	6.59 ^{ns}	6867.88 ^{ns}	0.76 ^{ns}
Doses of potassium (DK)	4	8125.15 ^{ns}	301265.71 ^{ns}	231166.02 ^{ns}	0.0018 ^{ns}	4.83 ^{ns}	7610.20 ^{ns}	0.72 ^{ns}
Linear regression	1	17777.92 ^{ns}	365955.20 ^{ns}	222414.50 ^{ns}	0.0001 ^{ns}	3.01 ^{ns}	2106.60 ^{ns}	0.50 ^{ns}
Quadratic regression	1	102.90 ^{ns}	7887.47 ^{ns}	6188.57 ^{ns}	0.00003 ^{ns}	2.81 ^{ns}	250.74 ^{ns}	2.30 ^{ns}
Interaction (SL × DK)	16	5625.69 ^{ns}	220322.71 ^{ns}	177477.35 ^{ns}	0.0011 ^{ns}	1.06 ^{ns}	2428.43 ^{ns}	1.28*
Blocks	2	287.05 ^{ns}	338995.25 ^{ns}	349617.00 ^{ns}	0.0070 ^{ns}	20.63**	34400.05*	30.30*
Residual	48	5111.22	184258.18	159257.55	0.0024	1.43	3880.37	0.67
CV		11.10	13.59	15.87	6.22	7.87	18.21	4.54

DF - degrees of freedom; CV (%) - coefficient of variation; * - significant at 0.05 probability level; ** - significant at 0.01 probability level; ^{ns} - not significant.

With regard to initial fluorescence (F_0) of okra plants, an increase from 592.77 (0.3 dS m^{-1}) to 717.01 (4.3 dS m^{-1}) was observed (Figure 5A). This increase in fluorescence emission in dark-adapted leaves, at ECw levels above 1.3 dS m^{-1} , may be indicative of partial inactivation of PSII reaction centers, preventing the energy absorbed by chlorophyll from being efficiently transferred to the reaction

center through the antenna complex (GALVÃO SOBRINHO et al., 2023). In a study by Sousa et al. (2023) on the hydroponic production of okra with the application of salicylic acid (SA), maximum F_0 values of 591.99 were recorded when the plants were grown in nutrient solution with ECw of 2.1 dS m^{-1} , values of the same order of magnitude as those obtained in the present experiment.

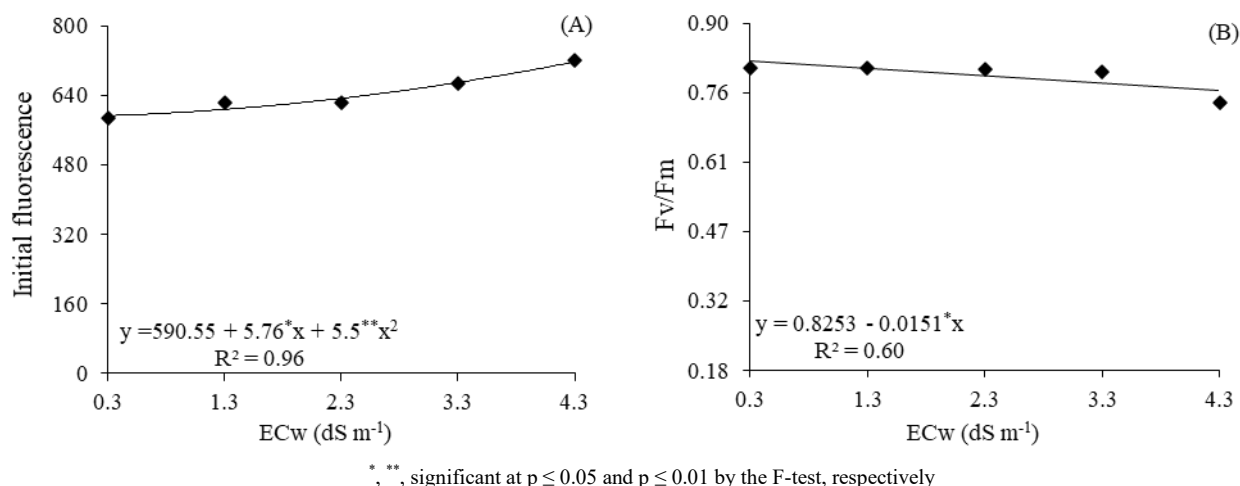


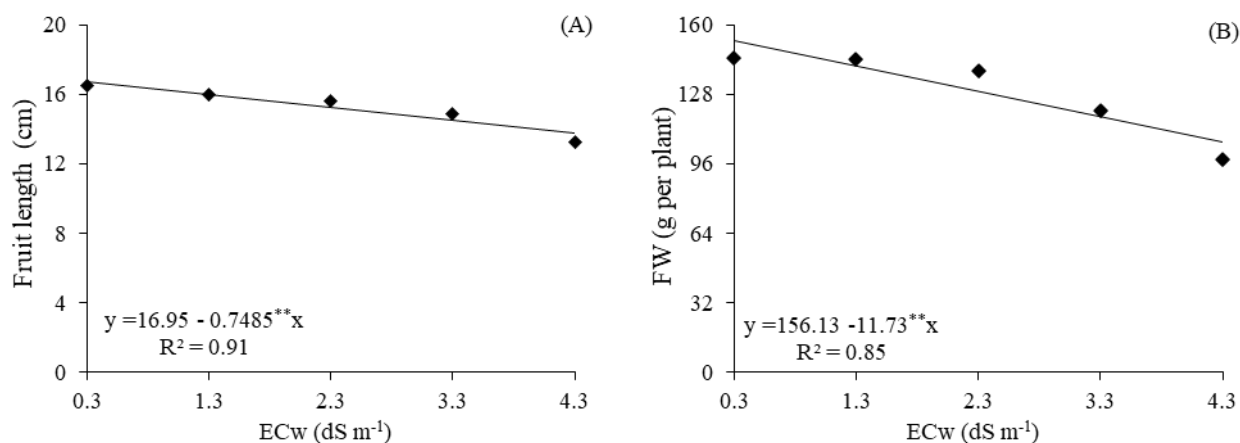
Figure 5. Initial fluorescence (F_0) (A) and quantum efficiency of photosystem II (F_v/F_m) (B) in okra cv. Santa Cruz as a function of irrigation water salinity levels (ECw).

An increase was observed in the quantum efficiency of photosystem II, with the highest efficiency (0.82) in plants irrigated with ECw of 0.30 dS m^{-1} . However, the F_v/F_m efficiency declined above this water salinity level, with the lowest value (0.76) recorded in plants under an ECw of 4.3 dS m^{-1} (Figure 5B). In this study, the F_v/F_m values obtained ranged from 0.76 to 0.82 in okra plants irrigated with ECw of 4.3 and 0.3 dS m^{-1} , respectively, indicating that the photosynthetic apparatus was intact and that there was no occurrence of photoinhibitory damage in the PSII reaction centers (BOLHAR-NORDENKAMPF et al., 1989), since F_v/F_m values between 0.75 and 0.85 are considered normal in plants cultivated in the absence of stress and express their maximum photosynthetic capacity (SILVA et al., 2015). Although it did not severely compromise the photosynthetic apparatus, the decrease in F_v/F_m from 0.82 to 0.76 possibly reflected physiological changes and lower photochemical efficiency in the okra plant.

Figure 6A depicts the fruit length (FL) of okra in response to increasing irrigation water salinity levels, with a reduction of 4.41% per unit increase in salinity. Plants irrigated with an ECw of 4.3 dS m^{-1} exhibited a 17.90% decrease in FL compared to those irrigated with an ECw of 0.3 dS m^{-1} . The decline in photosynthetic efficiency negatively impacts okra fruit morphology, as salinity disrupts energy metabolism. Stressed plants require high metabolic expenditure to sustain development, reducing fruit quality (BALASUBRAMANIAM et al., 2023). Under saline conditions, water absorption decreases, leading to ionic competition with K^+ and nutritional imbalances, which in turn

reduces photosynthesis, plant growth, leaf area, and fruit size and mass (NAJAFI; REZAEI; MOZAFARIAN, 2024). This trend aligns with findings by Soares et al. (2020), who reported a reduction in average fruit length in okra exposed to different salinity levels (ECw between 0.3 and 4.3 dS m^{-1}), regardless of potassium fertilization.

Fruit mass per plant also decreased with increasing irrigation water salinity. Plants irrigated with an ECw of 4.3 dS m^{-1} exhibited an average fruit mass of 105.69 g, representing a 30.74% reduction compared to plants irrigated with an ECw of 0.3 dS m^{-1} (152.61 g per plant) (Figure 6B). This decrease is attributed to increased salinity, which affects osmotic potential, increases the energy cost for maintaining metabolic activities, Na^+/K^+ competition at absorption sites, reduces stomatal conductance, and lowers the rate of carbon assimilation, resulting in less allocation of photoassimilates to the fruits (PINHEIRO et al., 2023). In a hydroponic okra cultivation system, Mendonça et al. (2022) observed a 3.82% decrease in average fruit weight per unit increase in nutrient solution ECw. Similarly, Roque et al. (2024), investigating hydrogen peroxide as an acclimation agent for okra plants under different salinity levels (0.3 to 4.3 dS m^{-1}), reported a reduction in this variable, with the highest fruit mass (18.39 g per plant) recorded in plants irrigated with an ECw of 0.3 dS m^{-1} . The divergence of the results obtained in the present study in relation to the study by Roque et al. (2024) may be related to the characteristics of the soil used, which directly influences the supply of salts in the soil and consequently the osmotic and ionic effects, the time of year and the number of harvests carried out per plant.



^{**}, significant at $p \leq 0.01$ by the F-test

Figure 6. Fruit length (A) and fresh fruit weight - FW (B) in okra cv. Santa Cruz as a function of irrigation water salinity levels (ECw).

Fruit diameter in okra increased from 17.30 mm in plants treated with 50% of the recommended K₂O dose and irrigated with an ECw of 0.3 dS m⁻¹ to 19.75 mm in those fertilized with 150% K₂O under an ECw of 4.3 dS m⁻¹. It is observed that plants grown under irrigation with high-salinity water had the effects of salt stress on fruit diameter mitigated by fertilization with the highest dose of potassium (Figure 7). This fact may be related to potassium's functions in the plant as an osmoregulatory agent, activator of antioxidant enzymes,

contributing to the reduction of lipid peroxidation of membranes mediated by oxidative stress (PRAVEEN; SINGH, 2024). A similar trend was reported by Soares et al. (2020), who observed that okra plants fertilized with potassium at 75, 100, and 125 mg kg⁻¹ exhibited increases of 9.14%, 20.8%, and 13.36%, respectively, in fruit diameter under an ECw of 4.3 dS m⁻¹ compared to those irrigated with an ECw of 0.3 dS m⁻¹.

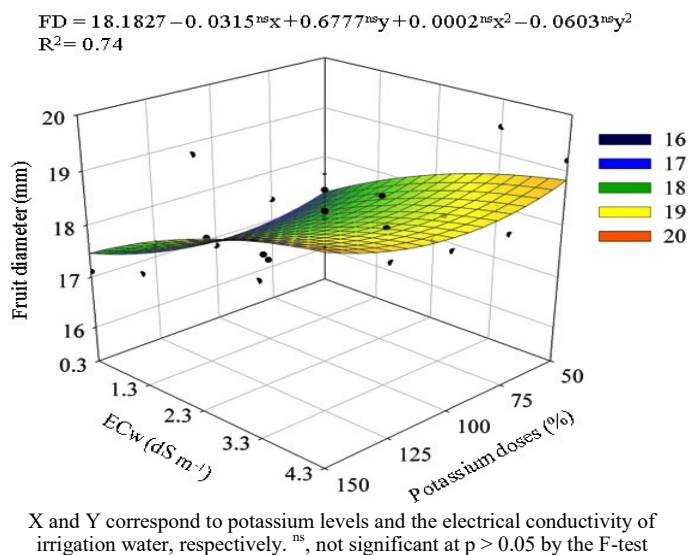


Figure 7. Fruit diameter in okra cv. Santa Cruz as a function of the interaction between irrigation water salinity levels and potassium doses.

CONCLUSIONS

Salinity levels above 0.3 dS m⁻¹ reduced the quantum efficiency of photosystem II, the length and mass fresh fruit weight of okra fruits cv. Santa Cruz. Fertilization with 150% of the recommended K₂O dose decreases stomatal conductance, transpiration, and the CO₂ assimilation rate of okra irrigated with water of 4.3 dS m⁻¹. Under semi-arid edaphoclimatic conditions, fertilization with 150% K₂O mitigated the effects of salt stress on the fruit diameter of okra

irrigated under an ECw of 4.3 dS m⁻¹.

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