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Scientific Article

Gas exchange, photochemical efficiency and growth of hydroponic okra under salt stress and salicylic acid

Trocas gasosas, eficiência fotoquímica e crescimento de quiabeiro hidropônico sob estresse salino e ácido salicílico

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ABSTRACT - Okra (*Abelmoschus esculentus* L.) is a shrub belonging to the Malvaceae family, which stands out for its rusticity and adaptation to soil and climatic conditions, being cultivated by small farmers, especially in the semi-arid region of Northeast Brazil. In this context, the objective of this study was to evaluate the effect of foliar application of salicylic acid as an attenuator of salt stress on leaf gas exchange, photochemical efficiency, and growth of okra cv. Canindé in a hydroponic system. The experiment was carried out using a Nutrient Film Technique - NFT hydroponic system in a greenhouse, in Pombal, PB, Brazil, from January to March 2022, in a completely randomized design, in a split-plot scheme, with the four levels of electrical conductivity of the nutrient solution - ECns (3.0, 5.0, 7.0, and 9.0 dS m^{-1}) considered as plots and four concentrations of salicylic acid – SA (0, 1.2, 2.4, and 3.6 mM) considered as subplots, with three replicates and two plants per plot. Increase in ECns levels from 3.0 dS m^{-1} inhibited leaf gas exchange, photochemical efficiency, and growth of okra cv. Canindé in hydroponic cultivation, at 34 days after transplanting. Foliar application of SA at concentrations of 2.2 and 1.5 mM promoted increments in stomatal conductance and transpiration, respectively. Salicylic acid at concentration of 1.9 mM associated with saline nutrient solution of 9.0 dS m^{-1} increased the variable fluorescence of okra plants cv. Canindé, at 34 days after transplantation.

Keywords: *Abelmoschus esculentus* L. Moench. Salinity. Soilless cultivation.Osmoregulation.

RESUMO - O quiabeiro (*Abelmoschus esculentus* L.) é um arbusto que pertencente à família Malvaceae, que se destaca pela rusticidade e adaptação às condições edafoclimáticas, sendo cultivado por pequenos agricultores, especialmente no semiárido do Nordeste do Brasil. Neste contexto, objetivou-se com este estudo avaliar o efeito da aplicação foliar de ácido salicílico como atenuante do estresse salino nas trocas gasosas foliares, eficiência fotoquímica e crescimento de quiabeiro cv. Canindé em sistema hidropônico. O trabalho foi desenvolvido em sistema hidropônico tipo Técnica de Fluxo de Nutrientes - NFT em casa de vegetação, em Pombal – PB, durante o período de janeiro a março de 2022, utilizando-se o delineamento inteiramente casualizado, em esquema parcelas subdivididas, sendo os quatro níveis de condutividade elétrica da solução nutritiva - CEsn (3,0; 5,0; 7,0 e 9,0 dS m^{-1}), considerados as parcelas e as quatro concentrações de ácido salicílico - AS (0; 1,2; 2,4 e 3,6 mM) as subparcelas com três repetições e duas plantas por parcela. O aumento dos níveis da solução nutritiva a partir de 3,0 dS m^{-1} inibiu as trocas gasosas foliares, a eficiência fotoquímica e o crescimento do quiabeiro cv. Canindé em cultivo hidropônico, aos 34 dias após o transplantio. A aplicação foliar nas concentrações de 2,2 e 1,5 mM de ácido salicílico proporcionaram aumento na condutância estomática e transpiração, respectivamente. O ácido salicílico na concentração de 1,9 mM associado à solução nutritiva salina de 9,0 dS m^{-1} elevou a fluorescência variável das plantas de quiabeiro cv. Canindé, aos 34 dias após o transplantio.

Palavras-chave: *Abelmoschus esculentus* L. Moench. Salinidade. Cultivo sem solo. Osmorregulação.

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INTRODUCTION

The semi-arid region of Northeast Brazil is characterized by high evapotranspiration rates and irregular rainfall throughout the year, thus contributing to water deficit and increased concentrations of salts in water (NOBRE et al., 2012; LIMA et al., 2018), resulting in limitations in crop growth and development, due to the decrease in osmotic and water potentials, which reduces water availability and nutrient absorption and transport (SILVA et al., 2022).

Salt stress causes metabolic and biochemical changes in plants, negatively affecting leaf gas exchange, protein synthesis, and enzymatic activity, which results in the intensification of chlorophyll degradation (LIANG et al., 2018). Salinity can also alter electron transport and modify the activity of photosystem II, which is responsible for the oxidation of water molecules to produce electrons (NAJAR et al., 2019).

In this region, hydroponic cultivation is a viable alternative for vegetable production and can reduce water consumption by up to 70% compared to conventional cultivation (in soil) and the environmental impacts caused by irrigation, providing precise control of pH, electrical conductivity and supply of nutrients to plants, in addition to reducing the effects of salt stress on plants due to the absence of matric potential (SAUSEN et al., 2020).

An alternative that has been used to reduce the effects of salt stress on plants is foliar application of salicylic acid (SA). SA is a natural phytohormone that participates in the activation of genes capable of acting on the plant's defense mechanism in the photosynthetic process and against oxidative damage, reducing the effects caused by salt stress (SILVA et al., 2023). In a study with cucumber cv. Hiroshi cultivated under nutrient solution salinity (2.1, 3.6, 5.1, and 6.6 dS m^{-1}) and salicylic acid, Oliveira et al. (2023) found that foliar application of SA at concentrations between 1.4 and 2.0 mM reduced the deleterious effect of salinity and promoted an increase in fruit production.

In view of the above, the objective of this study was to evaluate the effect of foliar application of salicylic acid as a mitigator of salt stress on leaf gas exchange, photochemical efficiency, and growth of okra cv. Canindé in an NFT hydroponic system.

MATERIAL AND METHODS

The experiment was conducted from January to March 2022 under greenhouse conditions, at the Center of Sciences and Agrifood Technology (CCTA), belonging to the Federal University of Campina Grande (UFCG), in the municipality of Pombal, PB, Brazil, geographically located at 6° 46' 8" South and 37° 47' 45" West, with an altitude of 184 m. According to Köppen's classification, the municipality of Pombal has a climate classified as semi-arid (hot and humid - AW') with a rainy season that begins in November and ends in April, with an average annual rainfall of 700 mm.

Data of temperature (maximum and minimum) and relative humidity were collected daily using a digital thermohygrometer inside the greenhouse and are presented in Figure 1.

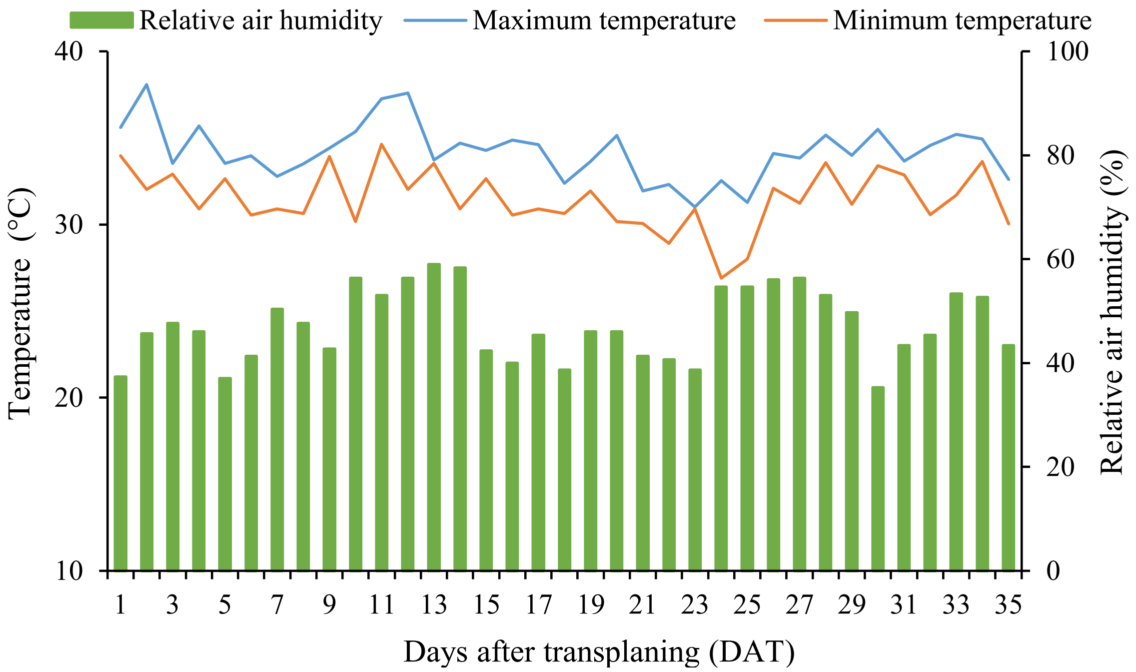


Figure 1. Daily data of temperatures (maximum and minimum) and average relative humidity of air during the experimental period (27/01 to 02/03/2022).

Treatments consisted of four levels of electrical conductivity of the nutrient solution - ECns (3.0, 5.0, 7.0, and 9.0 dS m^{-1}) and four concentrations of salicylic acid - SA (0, 1.2, 2.4, and 3.6 mM) distributed in a completely randomized design, in a split-plot scheme, with the ECns levels considered as the plots and the concentrations of salicylic acid as the subplots, with three replicates and two plants per plot. Salicylic acid concentrations were established based on the study by Silva et al. (2020), and ECns levels were defined based on the study conducted by Dantas et al. (2022) with zucchini.

The nutrient solution recommended by Hoagland and Arnon (1950) was used, and its composition and nutrient concentrations are shown in Table 1. The solution was prepared in local-supply water (0.3 dS m^{-1}), resulting in an electrical conductivity of 2.1 dS m^{-1}.

Table 1. Chemical composition of the nutrients present in the nutrient solution recommended by Hoagland and Arnon (1950), and fertilizers used in the hydroponic cultivation of okra cv. Canindé.

Nutrients	Fertilizers	Quantity (g 1000L^{-1})
P/K	KH_2PO_4	136.09
K/N	KNO_3	101.10
Ca /N	Ca $(NO_3)_2.4H_2O$	236.15
Mg/S	$MgSO_4.4H_2O$	246.49
B	H_3BO_3	3.10
Mn/S	$MnSO_4.4H_2O$	1.70
Zn/S	$ZnSO_4.7H_2O$	0.22
Cu/S	$CuSO_4$	0.75
Mo	$(NH_4)_6Mo_7O_{24}$. $4H_2O$	1.25
	EDTA – Na	13.9
Fe	$FeSO_4$	13.9

The saline nutrient solutions were prepared with the addition of non-iodized sodium chloride (NaCl), calcium chloride ($CaCl_2.2H_2O$), and magnesium chloride ($MgCl_2.6H_2O$) in an equivalent ratio of 7:2:1, respectively. Irrigation waters were prepared considering the relationship between ECw and salt concentration (RICHARDS, 1954), according to Equation 1:

$$Q \approx 10 \times ECw \tag{1}$$

Where:
Q = Sum of cations (mmol$_c$ L^{-1}); and
ECw = Desired electrical conductivity after discounting the ECw of the water of the municipal supply system (dS m^{-1}).

Seeds of okra cv. Canindé, a hybrid from ISLA® (Porto Alegre, Brazil) were used in the experiment. This cultivar has a cycle of approximately 80 days, with tall height, fruits with five ridges, with length between 10 and 15 cm and diameter ranging from 18 to 20 mm, in addition to excellent postharvest conservation, resistance to the Yellow Vein Mosaic virus (YVMV) and wide adaptability to different growing regions.

Okra seeds cv. Canindé were sown individually in 50 mL disposable containers containing coconut fiber substrate. Prior to sowing, the coconut fiber was washed to prevent salinization of the substrate. From germination until the appearance of the second pair of true leaves, plants received nutrient solution with a concentration of 50% of the recommendation of Hoagland and Arnon (1950), then the coconut fiber was removed from the root system, and the plants were inserted directly into the hydroponic profiles, supported vertically with nylon twine to leave the stem erect, and received nutrient solution with 100% concentration.

The hydroponic system was of the Nutrient Film Technique (NFT) type, made with a 100-mm-diameter PVC pipe, as shown in Figure 2. The spacing was 0.50 m between plants in the channel and 1.0 m between treatments.

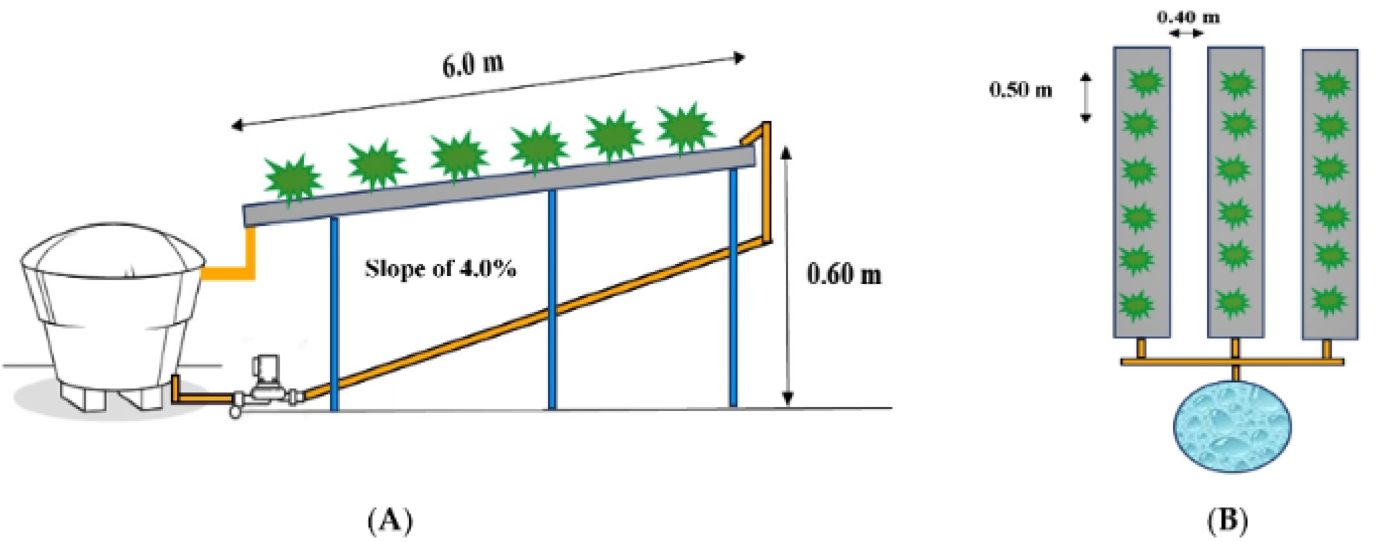


Figure 2. Side view (A) and top view (B) of the hydroponic system used in the study. Source: Oliveira et al. (2023).

The channels were supported on sawhorses with 0.60 m height and slope of 4% to allow adequate flow of the nutrient solution. At the lowest level of each bench of the hydroponic system, a 150 L polyethylene box was placed to collect and conduct the nutrient solution to the channels. The nutrient solution was pumped to the channel head by a pump with power of 35 W and average flow rate of 3 L min^{-1}. Nutrient solution circulation was programmed by a timer, with an intermittent flow of 15 min during the day and night.

The nutrient solution was fully replaced every eight days, with daily checks of electrical conductivity and pH, and adjustment of the solution whenever necessary, through the addition of local-supply water with ECw of 0.3 dS m^{-1}, always maintaining the ECns according to the preestablished treatments, and the pH was maintained within the range between 5.5 and 6.5 through the addition of 0.1 M KOH.

Salicylic acid concentrations were prepared by dissolving salicylic acid (A.R.) in 30% ethyl alcohol (99.5%) and 0.05% Haiten®, a nonionic adhesive spreader used to break the surface tension and improve absorption by okra leaves. Salicylic acid applications were carried out 48 hours after inserting the plants in the hydroponic profiles and 72 hours before the beginning of the use of saline nutrient solutions. The applications were carried out at 5:00 p.m., with a manual sprayer, so as to moisten all the area of the leaves (adaxial and abaxial sides) according to the treatments, applying on an average 19 mL per plant, at 8-day intervals, totaling four applications. A cardboard structure was used to avoid the drift of the treatments between the plants. Plants were monitored and phytosanitary practices were carried out whenever necessary.

At 34 days after transplanting (DAT), leaf gas exchange was evaluated by the determination of stomatal conductance - *gs* (mol H_2O m^{-2} s^{-1}), transpiration - *E* (mmol H_2O m^{-2} s^{-1}), CO_2 assimilation rate - A (µmol CO_2 m^{-2} s^{-1}), internal CO_2 concentration - Ci (µmol CO_2 m^{-2} s^{-1}), initial fluorescence (F_0), maximum fluorescence (F_m), variable fluorescence (F_v), quantum efficiency of photosystem II in the dark phase (F_v/F_m), initial fluorescence before saturation pulse (F_s), maximum fluorescence after adaptation to saturating light (F_{ms}), quantum efficiency of photosystem II in the light phase (Y), and electron transport rate (ETR), and growth was evaluated through plant height (PH), stem diameter (SD), number of leaves (NL), and leaf area (LA).

Gas exchange was determined in leaves located in the middle third with a portable infrared carbon dioxide analyzer (IRGA), model LCPro$^+$ Portable Photosynthesis System® (ADC BioScientific Limited, UK), with irradiation of 1200 µmol photons m^{-2} s^{-1} and air flow of 200 mL min^{-1}, and atmospheric CO_2 concentration.

The photochemical efficiency of okra plants was determined by means of initial fluorescence (F_0), maximum fluorescence (F_m), variable fluorescence (F_v), quantum efficiency of photosystem II in the dark phase (F_v/F_m), initial fluorescence before saturation pulse (F_s), maximum fluorescence after adaptation to saturating light (F_{ms}), quantum efficiency of photosystem II in the light phase (Y) and electron transport rate (ETR). Chlorophyll fluorescence in the dark phase was measured in fully expanded leaves of the middle third, pre-adapted to the dark for 30 min, using an OS5p modulated-pulse fluorometer from Opti Science.

The pulse of light used was low-intensity modulated red (0.03 µmol m^{-2} s^{-1}), followed by a pulse of saturated actinic light (> 6000 µmol m^{-2} s^{-1}). Subsequently, the determinations were performed under light conditions, using the Yield protocol, applying an actinic light source with a saturating multi-flash pulse coupled to a clip to determine photosynthetically active radiation (PAR-Clip).

Stem diameter was measured at 5 cm from the hydroponic profile, with a digital caliper. Plant height was obtained by taking as reference the distance from the hydroponic profile to the insertion of the apical meristem, with the aid of a graduated ruler. In the quantification of the number of leaves, only those with minimum length of 3 cm and at least 50% of their leaf area photosynthetically active were considered. Leaf area was measured with a graduated ruler, and the values were established according to Fideles Filho, Beltrão and Pereira et al. (2010), using Equation 2:

$$Y = \sum 0.7254\,(\chi)^{2.08922} \qquad (2)$$

Where:
Y = leaf area of the plant (cm^2); and
χ = midrib length (cm).

The data obtained were subjected to the normality test (Shapiro-Wilk), and later analysis of variance was performed by the F test at $p \leq 0.05$ probability level. When significant, polynomial regression analysis was performed for the saline nutrient solution and salicylic acid concentrations, using the statistical software SISVAR – ESAL (FERREIRA, 2019). SigmaPlot® software was used to construct the response surface curves in cases of significant interaction between the factors.

RESULTS AND DISCUSSION

There was a significant effect of the salinity levels of the nutrient solution on stomatal conductance (*gs*), transpiration (*E*), CO_2 assimilation rate (*A*), and internal CO_2 concentration (*Ci*) in okra plants cv. Canindé at 34 days after transplanting (Table 2). The concentrations of salicylic acid significantly influenced the stomatal conductance (*gs*) and transpiration (*E*) of okra plants cv. Canindé. There was no interactive effect of the factors (ECns × SA) for any of the variables analyzed in okra cv. Canindé, at 34 days after transplantation.

Table 2. Summary of the analysis of variance for stomatal conductance (*gs*), internal CO_2 concentration (*Ci*), transpiration (*E*), and CO_2 assimilation rate *(A)* of okra plants cv. Canindé cultivated under saline nutrient solution (ECns) and exogenous application of salicylic acid (SA) at 34 days after transplanting.

Sources of variation	Mean squares				
	DF	*gs*	*Ci*	*E*	*A*
Saline nutrient solution (ECns)	3	0.24^{**}	7225.59^{**}	15.10^{**}	975.85^{**}
Linear regression	1	0.67^{**}	1627.60^{ns}	39.43^{**}	2037.99^{**}
Quadratic regression	1	0.007^{ns}	19967.52^{**}	0.67^{ns}	876.80^{**}
Residual 1	8	0.0015	519.7	0.105	17.62
Salicylic acid (SA)	3	0.02^{**}	48.12^{ns}	1.04^{*}	69.71^{ns}
Linear regression	1	0.035^{**}	42.50^{ns}	0.67^{ns}	66.96^{ns}
Quadratic regression	1	0.019^{*}	58.52^{ns}	2.14^{**}	73.28^{ns}
Interaction (ECns × SA)	9	0.006^{ns}	1189.17^{ns}	0.23^{ns}	18.91^{ns}
Residual 2	24	0.00325	376.75	0.25	15.69
CV 1(%)		8.15	20.64	5.46	9.77
CV 2(%)		12.00	17.57	8.43	9.22

DF - degrees of freedom; CV1 and CV2 (%), coefficient of variation; **significant at 0.01 probability level; *significant at 0.05 probability level; ^{ns} not significant.

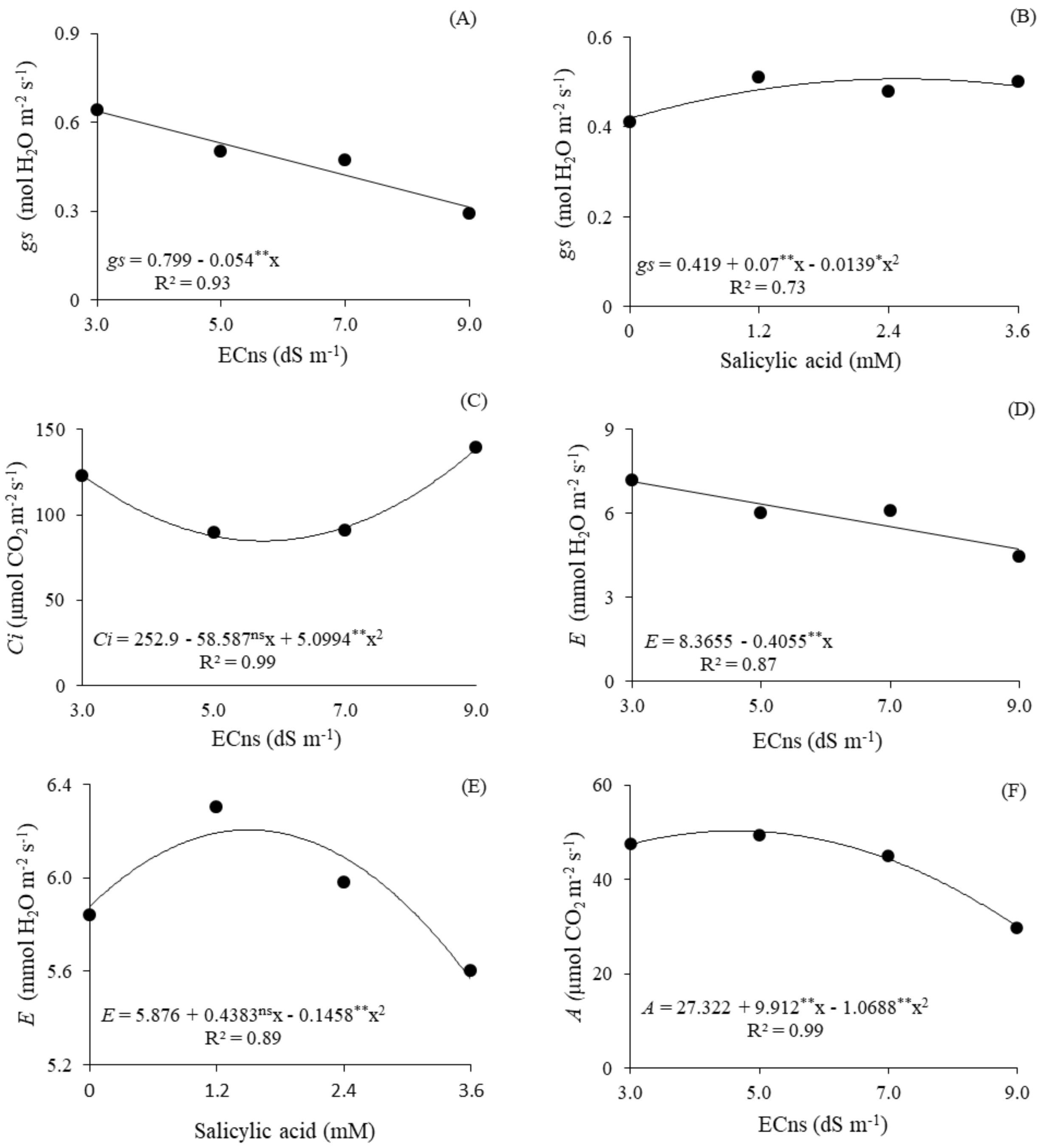
The stomatal conductance of okra plants was affected negatively with the increase in nutrient solution salinity (Figure 3A), with decreases of 6.75% per unit increment of ECns. When comparing the *gs* of plants subjected to ECns of 9.0 dS m^{-1} to that of plants that received 3.0 dS m^{-1} irrigation water, a decline of 50.86% was observed. Stomatal closure is a strategy that aims to minimize the loss of water to the atmosphere and maintain water balance, resulting in a reduction in the absorption of toxic ions (DIAS et al., 2019). The negative effect of water salinity was also reported by Veloso et al. (2021), who evaluated bell pepper cv. All Big cultivated with ECw (0.8, 1.6, 2.4, and 3.2 dS m^{-1}) and observed a reduction of 11.65% per unit increase in stomatal conductance at 80 days after sowing.

Regarding the effect of foliar application of salicylic acid on stomatal conductance (Figure 3B), it was observed that okra cv. Canindé subjected to SA concentration of 2.5 mM obtained the maximum estimated value of 0.51 mol H_2O m^{-2} s^{-1}. On the other hand, the minimum value of *gs* (0.42 mol H_2O m^{-2} s^{-1}) was observed in plants subjected to SA concentration of 0 mM. Under conditions of salt stress, SA contributes to reducing Na^+ contents and can increase K^+ content of leaves and roots, besides stimulating the activity of ribulose-1,5-bisphosphate carboxylase-oxygenase (RuBisCO), thus favoring K absorption and ATP content, maintaining the proper ratio in plants, and consequently their tolerance to salt stress (OLIVEIRA; PEREIRA; ROH, 2014). Corroborating the results obtained in this study, Oliveira et al. (2023) evaluated the gas exchange of cucumber plants using saline nutrient solutions and salicylic acid in a hydroponic system and also found the highest stomatal conductance value (0.305 mol H_2O m^{-2} s^{-1}) under ECns of 2.1 dS m^{-1} and SA concentration of 2.0 mM.

For the internal CO_2 concentration – *Ci* (Figure 3C), it is observed that plants under electrical conductivity of the nutrient solution of 9.0 dS m^{-1} reached the maximum estimated value of 138.67 µmol CO_2 m^{-2} s^{-1}, while the lowest *Ci* of 84.63 µmol CO_2 m^{-2} s^{-1} was obtained in plants cultivated under ECns of 5.7 dS m^{-1}, with a reduction of 38.97% between ECns levels of 3.0 and 5.7 dS m^{-1}. The increase in internal CO_2 concentration may be associated with a decrease in the activity of the RuBisCO enzyme and deterioration of the photosynthetic system in response to leaf tissue senescence, resulting from the pressure caused by the excessive accumulation of salts (DIAS et al., 2018).

The transpiration – *E* of okra plants was linearly reduced with the increase in ECns, by 4.85% per unit increment in ECns (Figure 3D), i.e., a reduction of 34.03% between plants cultivated under ECns of 3.0 and 9.0 dS m^{-1}. The partial closure of the stomata restricts leaf transpiration due to the reduction in the osmotic potential of the soil solution. However, the reduction of transpiration can be considered a strategy to avoid excessive absorption of salts, especially toxic ones, but prolonged stress can impair plant growth and production (DIAS et al., 2018).

For the transpiration – *E* (Figure 3E) of okra, it is observed that plants under SA concentration of 1.5 mM reached the maximum estimated value of 6.21 mmol H_2O m^{-2} s^{-1}, while plants subjected to SA concentration of 3.6 mM had an *E* of 5.56 mmol H_2O m^{-2} s^{-1}. The beneficial effect of SA is related to its role as a signaling molecule, activating the defense system of plants, especially the processes of osmoregulation, elimination of reactive oxygen species (ROS) and maintenance of ionic homeostasis. SA can also stimulate chlorophyll biosynthesis and/or reduce its degradation (SILVA et al., 2020). The results of this study are in agreement with those reported by Silva et al. (2022), who evaluated the effects of salt stress on cherry tomato plants grown in soil and observed reductions in leaf gas exchange from 2.6 dS m^{-1}, at 100 days after transplanting.



*, ** - Significant at $p \leq 0.05$ and ≤ 0.01 by the F test, respectively.

Figure 3. Stomatal conductance - *gs* (A), internal CO_2 concentration - *Ci* (C), transpiration - *E* (D), CO_2 assimilation rate - *A* (F) of okra cv. Canindé, as a function of saline nutrient solution - ECns and stomatal conductance - *gs* (B) and transpiration - *E* (E) as a function of the concentrations of salicylic acid in okra cv. Canindé in a hydroponic system, at 34 days after transplanting.

For the CO_2 assimilation rate – *A* (Figure 3F) of okra, it was observed that plants under electrical conductivity of the nutrient solution of 4.6 dS m^{-1} reached the maximum estimated value (50.30 µmol CO_2 m^{-2} s^{-1}), while those cultivated with ECns of 9.0 dS m^{-1} had an *A* of 29.96 µmol CO_2 m^{-2} s^{-1}, with a reduction of 40.44% between ECns levels of 4.6 and 9.0 dS m^{-1}. High ECns levels induce partial closure of stomata and restrict CO_2 diffusion in the substomatal chamber (LIMA et al., 2020), besides inhibiting the activity of RuBisCO, which predisposes the photosynthetic apparatus to increased energy dissipation and downregulation of photosynthesis when plants are subjected to salt stress

(SILVA et al., 2018). Oliveira et al. (2022) also observed that nutrient solution salinity of 5.4 dS m^{-1} and foliar application of SA at concentration of 4.5 mM caused a minimum value of 14.33 μmol CO_2 m^{-2} s^{-1} in the CO_2 assimilation rate of melon in a hydroponic system, at 56 days after transplanting.

There was a significant effect of saline nutrient solution (ECns) on the initial fluorescence (F_0), maximum fluorescence (F_m), maximum quantum efficiency of photosystem II (F_v/F_m) and quantum efficiency of photosystem II (Y) of okra cv. Canindé (Table 3). SA concentrations did not significantly influence (p>0.05) any of the variables measured in okra cv. Canindé. The interaction between the factors (ECns × SA) significantly affected the variable fluorescence (F_v) of okra plants cv. Canindé.

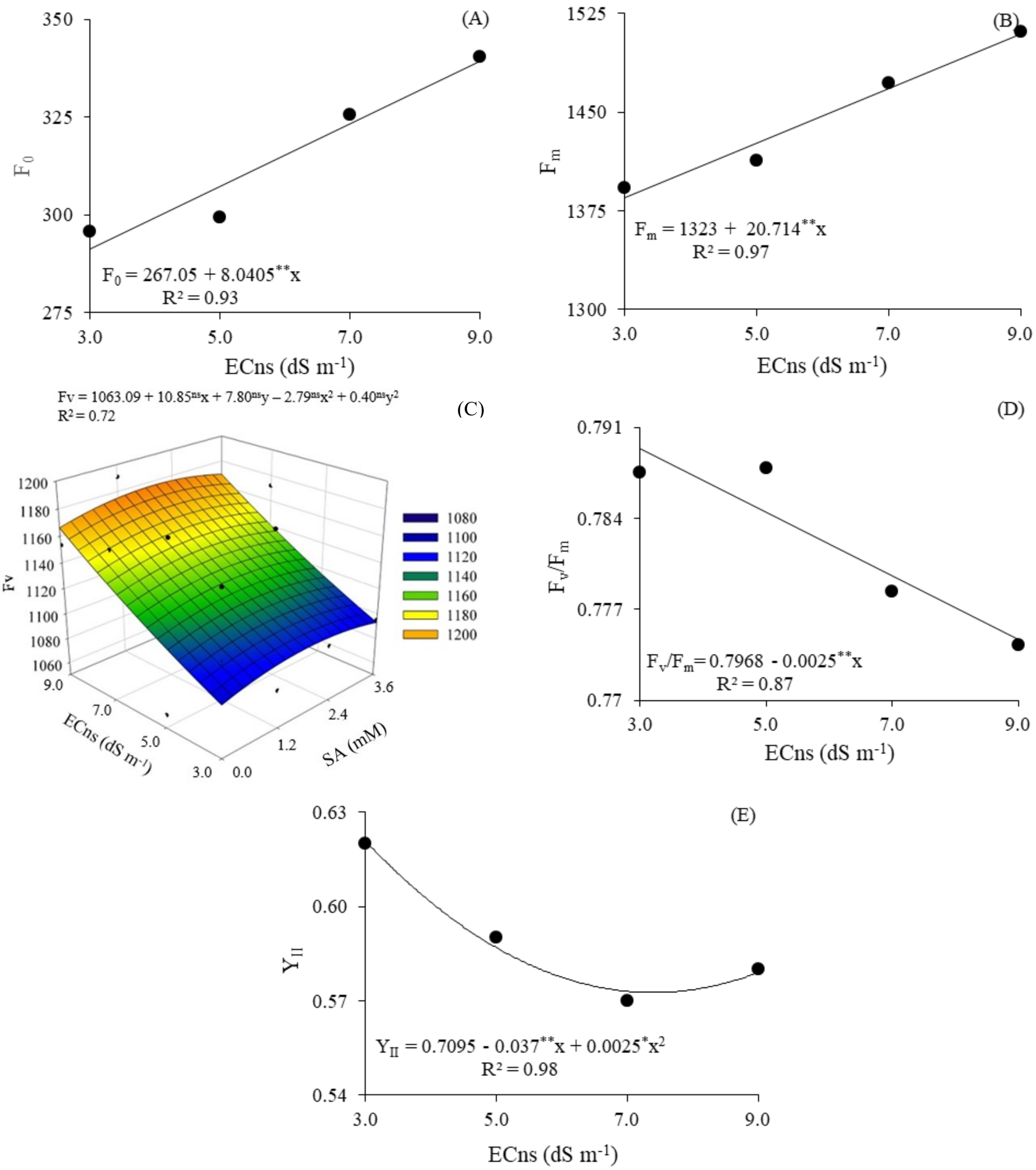
Table 3. Summary of the analysis of variance for initial fluorescence (F_0), maximal fluorescence (F_m), variable fluorescence (F_v), quantum efficiency of photosystem II in the dark phase (F_v/F_m), initial fluorescence before saturation pulse (F_s), maximum fluorescence after adaptation to saturating light (F_{ms}), quantum efficiency of photosystem II in the light phase (Y) and electron transport rate (ETR) of okra cv. Canindé cultivated under saline nutrient solution (ECns) and concentrations of salicylic acid (SA) in a hydroponic system at 34 days after transplanting.

Sources of variation	DF	Mean squares			
		F_0	F_m	F_v	F_v/F_m
Saline nutrient solution (ECns)	3	5530.06**	35304.35**	13004.36**	0.0005**
Linear regression	1	15512.37**	102982.55**	38557.35**	0.0014**
Quadratic regression	1	382.50ns	949.63ns	126.75ns	0.00006ns
Residual 1	8	115.31	1241.98	688.76	0.000067
Salicylic acid (SA)	3	282.81ns	979.04ns	612.35ns	0.00008ns
Linear regression	1	204.42ns	47.25ns	55.10ns	0.00007ns
Quadratic regression	1	231.88ns	159.50ns	776.02ns	0.0001ns
Interaction (ECns × SA)	9	113.08ns	4901.41ns	3949.12*	0.00006ns
Residual 2	24	431.50	4355.95	2596.27	0.000076
CV 1(%)		3.41	2.43	2.68	0.55
CV 2(%)		6.59	4.56	4.32	1.1
		F_s	F_{ms}	Y	ETR
Saline nutrient solution (ECns)	3	32.17ns	583.51ns	0.0047*	90.30ns
Linear regression	1	86.40ns	323.17ns	0.0081**	18.17ns
Quadratic regression	1	0.52ns	1276.17ns	0.0057*	219.09ns
Residual 1	8	21.97	201.11	0.000375	59.63
Salicylic acid (SA)	3	39.22ns	313.25ns	0.0003ns	14.71ns
Linear regression	1	50.41ns	736.75ns	0.0005ns	42.29ns
Quadratic regression	1	21.33ns	194.00ns	0.00006ns	1.52ns
Interaction (ECns × SA)	9	32.69ns	382.01ns	0.0014ns	46.59ns
Residual 2	24	23.79	451.38	0.0013	51.58
CV 1(%)		8.01	9.75	4.08	15.84
CV 2(%)		6.93	12.15	5.9	12.26

DF - degrees of freedom; CV1 and CV2 (%), coefficient of variation; **significant at 0.01 probability level; *significant at 0.05 probability level; ns not significant.

The initial fluorescence – F_0 (Figure 4A) and maximum fluorescence – F_m (Figure 4B) of okra increased linearly with the increase in nutrient solution salinity, with increments of 3.01 and 1.50% per unit increase in ECns, respectively. In relative terms, F_0 and F_m increased by 16.57 and 8.97% in plants subjected to the highest level of nutrient solution salinity (9.0 dS m^{-1}) compared to those under the lowest ECns (3.0 dS m^{-1}), respectively. Initial fluorescence is an indicator of the oxidation capacity of quinone, the primary electron receptor in the reaction center of photosystem II (PSII). Under conditions of salt stress, initial fluorescence (F_0) tends to increase in plants, which highlights the impact of stress caused by high concentrations of salts (LIMA et al., 2019).

Salt stress results in significant damage to plants when they are exposed to these conditions, especially when the time of exposure to the soluble salts present in irrigation water is prolonged. The increase in F_0 is indicative of destruction of the reaction centers of the photosystem or decrease in the capacity to transfer excitation energy from the antenna to PSII, caused by salinity (SÁ et al., 2018). On the other hand, the increase in the dissipation of excess energy observed in this study through F_m can be considered a mechanism of release and regulation of PSII, a situation that enables the closure of reaction centers, preserving the cycles of xanthophyll and lutein (ZEGADA-LIZARAZU; LUNA; MONTI, 2015).



*, ** - Significant at $p \leq 0.05$ and ≤ 0.01 by the F test, respectively. Figure C -. X and Y - Concentration of salicylic acid - SA and electrical conductivity of the nutrient solution - ECns, respectively;

Figure 4. Initial fluorescence - F_0 (A), maximum fluorescence - F_m (B), quantum efficiency of photosystem II in the dark phase - F_v/F_m (D) and quantum efficiency of photosystem II in the light phase - Y (E) of okra cv. Canindé, as a function of saline nutrient solution - ECns and response surface for variable fluorescence - F_v (C) as a function of the interaction between salicylic acid - SA and ECns, in a hydroponic system, at 34 days after transplanting.

For variable fluorescence - F_v (Figure 4C), it was observed that plants subjected to ECns of 9.0 dS m^{-1} and SA concentration of 1.9 mM obtained the highest estimated value (1176.23). On the other hand, the lowest value of F_v (1090.09) was obtained in plants cultivated under salicylic acid concentration of 0 mM and ECns of 3.0 dS m^{-1}. This variable reflects the plant's efficiency in transferring the energy of electrons ejected from pigment molecules to the formation of the NADPH reducer, ATP, and reduced ferredoxin (Fdr) (LIMA et al., 2019). The increase observed in F_v, as a result of the increase in SA application, suggests a greater tolerance of the plants and, consequently, a possible protection against potential stress situations.

The quantum efficiency of photosystem II in the chemical phase - F_v/F_m of okra plants decreased linearly with the increase in the electrical conductivity of the nutrient solution, by 0.31% per unit increase in ECns (Figure 4D). When comparing the F_v/F_m of plants subjected to ECns of 9.0 dS m^{-1} to that of plants that received the lowest ECns (3.0 dS m^{-1}), a reduction of 1.9% was observed. In general, plants subjected to salt stress show reduction in the maximum quantum efficiency of photosystem II (F_v/F_m), as observed in the present study. This reduction in quantum efficiency of photosystem II (PSII) in plants cultivated with brackish waters suggests the occurrence of photoinhibitory damage to the reaction centers of PSII, leading to the formation of ROS, consequently affecting plant metabolism (LIMA et al. 2019).

The highest value of quantum efficiency of photosystem II – Y in the photochemical phase (0.62) was obtained in plants under saline nutrient solution of 3.0 dS m^{-1}, with a decrease from this level, reaching the minimum value of 0.57 in plants subjected to the estimated ECns of 7.4 dS m^{-1}, corresponding to a reduction of 7.79% in comparison with plants that reached the highest value of Y (Figure 4E). The photosynthetic performance of plants subjected to increasing salt concentrations in the nutrient solution can be evaluated by the effective quantum yield of photosystem II (Y(II)). Lower values of this parameter in plants subjected to higher salt concentrations indicate reduction in photosynthesis rate. Similar results were observed by Tatagiba et al. (2014) in a study with tomato cv. Santa Clara subjected to saline nutrient solution (0, 50, 100, and 150 mmol L^{-1} of NaCl), in which the authors found a significant reduction in the quantum efficiency of photosystem II in plants subjected to 150 mmol L^{-1} of NaCl compared to control plants (0 mmol L^{-1} of NaCl).

There were significant effects of saline nutrient solution on plant height (PH), stem diameter (SD), number of leaves (NL), and leaf area (LA) of okra plants cv. Canindé (Table 4). SA concentrations and the interaction between the factors (ECns × SA) did not significantly influence any of the growth variables of okra cv. Canindé, at 34 days after transplantation (Table 4).

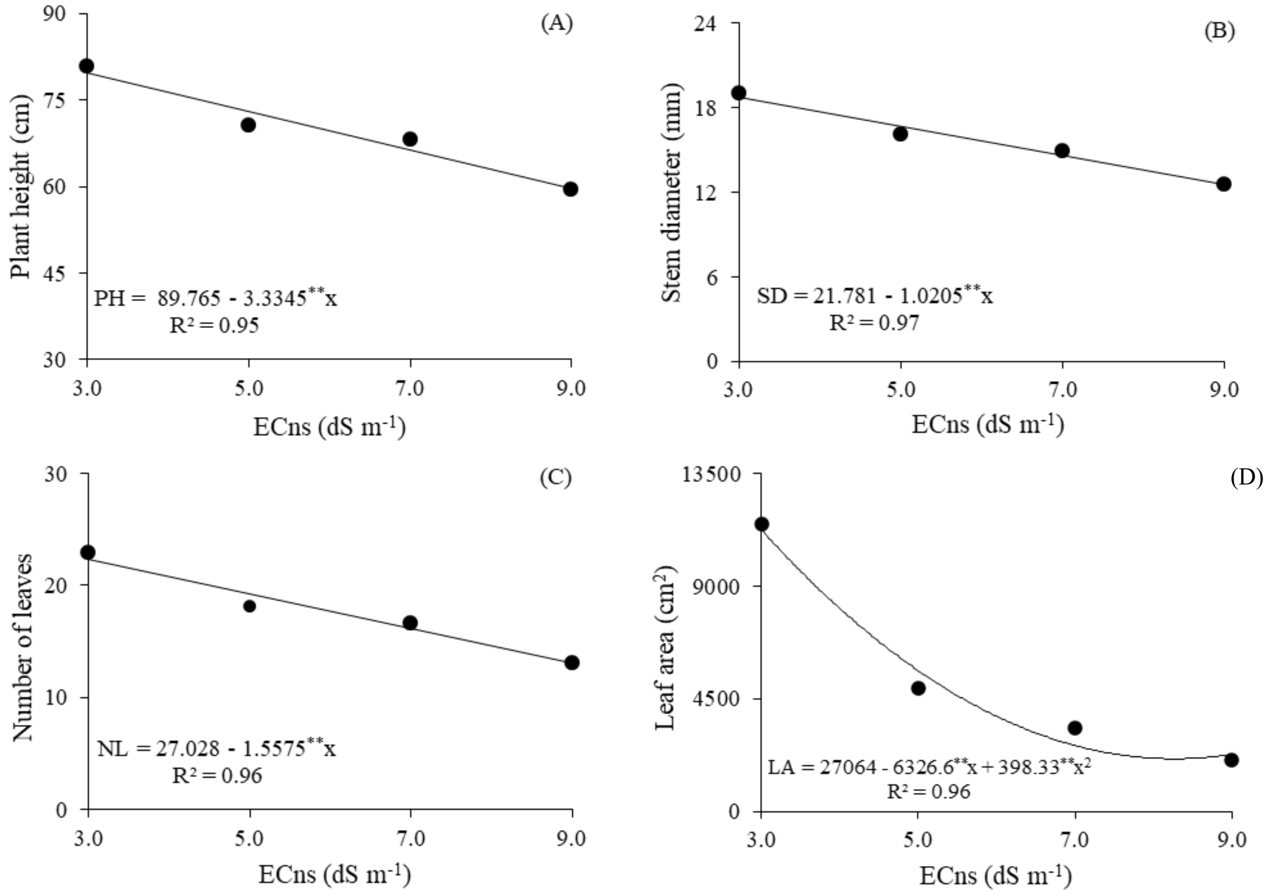
Table 4. Summary of the analysis of variance for plant height (PH), stem diameter (SD), number of leaves (NL), and leaf area (LA) of okra plants cv. Canindé cultivated under saline nutrient solution (ECns) and application of salicylic acid (SA), at 34 days after transplanting.

Sources of variation	Mean squares				
	DF	PH	SD	NL	LA
Saline nutrient solution (ECns)	3	930.04**	85.59**	201.56**	212114569.00**
Linear regression	1	2670.00**	250.12**	582.81**	539704090.54**
Quadratic regression	1	8.75ns	1.02ns	5.33ns	83686080.53**
Residual 1	8	63.07	5.67	4.45	794155.30
Salicylic acid (SA)	3	57.08ns	0.42ns	1.85ns	2593428.32ns
Linear regression	1	122.55ns	0.79ns	4.53ns	7383880.45ns
Quadratic regression	1	11.50ns	0.30ns	1.02ns	247326.60ns
Interaction (ECns × SA)	9	67.54ns	3.93ns	6.11ns	3390145.42ns
Residual 2	24	81.12	6.06	8.20	1162664.70
CV 1(%)		11.38	15.21	11.93	16.34
CV 2(%)		12.91	15.72	16.19	19.77

DF - degrees of freedom; CV1 and CV2 (%), coefficient of variation; **significant at 0.01 probability level; ns not significant.

Okra growth was negatively affected by the increase in nutrient solution salinity, with linear decreases in plant height, stem diameter, and number of leaves, equal to 3.71, 4.68, and 5.76% per unit increase of ECns, respectively (Figures 5A, 5B and 5C). High concentrations of salts present in the nutrient solution tend to disturb the ionic balance, damaging the metabolism of plants, causing oxidative stress, damaging plant tissues, thus leading to a reduction in the height of okra plants cv. Canindé (CHRYSARGYRIS et al., 2019). Such reduction was reported by Modesto et al. (2019), who observed that the growth of okra plants cv. Speedy was affected by the increase in salinity from 1.8 dS m^{-1}, at 101 days after sowing.

The leaf area of okra plants decreased from ECns of 3.0 dS m^{-1} (11669.17 cm^2), with a minimum value of 1943.64 cm^2 in plants subjected to ECns of 7.9 dS m^{-1}, corresponding to a reduction of 83.34% compared to plants that reached the highest LA value (Figure 5D). Inhibition in LA growth stands out as a mechanism of tolerance to salt stress and is a strategy to maintain high leaf water potential and reduce excessive absorption of toxic ions. The reduction observed in the LA of okra plants under salt stress is related to the increase in ROS, which cause biochemical disturbances and physiological changes with the decrease in stomatal opening (LIMA et al., 2020), as observed in Figure 3 (A, B, C, D, E, and F) of the present study. Dantas et al. (2022), in a study with zucchini in a hydroponic system using saline nutrient solutions (ECns: 2.1, 3.6, 5.1, and 6.6 dS m^{-1}), also observed a marked reduction in leaf area at 47 days after transplanting from 2.1 dS m^{-1}.



*, ** - Significant at $p \leq 0.05$ and ≤ 0.01 by the F test, respectively.

Figure 5. Plant height – PH (A), stem diameter – SD (B), number of leaves - NL (C), and leaf area - LA (D) of okra plants cv. Canindé in hydroponic cultivation, as a function of saline nutrient solution - ECns, at 34 days after transplanting.

CONCLUSIONS

Increase in the levels of electrical conductivity of the nutrient solution above 3.0 dS m^{-1} inhibits leaf gas exchange, initial and maximum fluorescence, quantum efficiency of photosystem II in the chemical and in the photochemical phase and growth of okra cv. Canindé in hydroponic cultivation, at 34 days after transplanting. Foliar application of salicylic acid at concentrations of 2.2 and 1.5 mM increases the stomatal conductance and transpiration of hydroponic okra plants. Foliar application of salicylic acid at concentration of 1.9 mM associated with saline nutrient solution of 9.0 dS m^{-1} increases variable fluorescence in okra plants cv. Canindé.

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