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Physiological aspects and production of coriander using nutrient solutions prepared in different brackish waters[1]

Aspectos fisiológicos e produção do coentro sob soluções nutritivas preparadas em diferentes águas salobras

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HIGHLIGHTS:

Differences caused by cationic natures are even more evident than an increase in concentration up to a certain threshold.
The prevalence of Na^+ in water caused less damage to the photosynthetic apparatus than the prevalence of Ca^{2+} or Mg^{2+}.
There is no influence of the cationic nature at high levels of salt concentration in the nutrient solution.

ABSTRACT: The analysis of chlorophyll fluorescence is one of many ways to quantify the salt damage to photosynthetic performance and crop production. Thus, the present study aimed to evaluate the photochemical efficiency and production of coriander, cultivar 'Verdão', as a function of the electrical conductivity levels of the nutrient solution and the cationic nature. The experimental design was in randomized blocks, in a 4 × 3 factorial scheme, with four replicates. The treatments consisted of four electrical conductivities of the nutrient solutions (ECns = 1.6, 3.2, 4.8, and 6.4 dS m^{-1}) and three kinds of water of different cationic natures (Na^+; Ca^{2+}; Mg^{2+}), which were prepared with the dissolution of different salts - NaCl, $CaCl_2.2H_2O$, and $MgCl_2.6H_2O$ in supply water (ECw = 0.12 dS m^{-1}), that is, three predominant cationic natures. The study was carried out in a greenhouse between November and December 2019 at the Fertigation and Salinity Laboratory of the Agricultural Engineering Department of the Universidade Federal Rural de Pernambuco. It was found that the increase in the electrical conductivity of the nutrient solution affected reaction centers, photochemical activity, and carboxylation efficiency and resulted in reductions in stomatal conductance, CO_2 assimilation rate, and therefore, in the biomass production of coriander. Different cationic prevalence in water causes differences in the intensity of salt damage, especially with increasing concentration.

Key words: *Coriandrum sativum* L., gas exchange, chlorophyll a fluorescence

RESUMO: A análise da fluorescência da clorofila é uma das muitas formas de quantificar o dano salino no desempenho fotossintético e na produção agrícola. Assim, o presente estudo teve como objetivo avaliar a eficiência fotoquímica e a produção do coentro, cultivar Verdão em função dos níveis de condutividades elétricas da solução nutritiva e da natureza catiônica. O delineamento experimental foi em blocos ao acaso, em esquema fatorial 4 × 3, com quatro repetições. Os tratamentos consistiram na exposição das plantas a quatro condutividades elétricas das soluções nutritivas (CEsn = 1,6; 3,2; 4,8 e 6,4 dS m^{-1}) e três tipos de águas de diferentes naturezas catiônicas (Na^+; Ca^{2+}; Mg^{2+}), preparadas com a solubilização de diferentes sais - NaCl, $CaCl_2.2H_2O$ e $MgCl_2.6H_2O$ em água de abastecimento da UFRPE (CEa = 0,12 dS m^{-1}). O estudo foi realizado em casa de vegetação entre novembro e dezembro de 2019 no Laboratório de Fertirrigação e Salinidade do Departamento de Engenharia Agronômica da Universidade Federal Rural de Pernambuco. O aumento da condutividade elétrica da solução nutritiva afetou os centros de reação, a atividade fotoquímica, a eficiência da carboxilação e resultou na redução da condutância estomática, da taxa de assimilação de CO_2 e, portanto, na produção de biomassa do coentro. Diferentes prevalências catiônicas na água proporcionam diferenças na intensidade do dano salino, sobretudo com o aumento da concentração.

Palavras-chave: *Coriandrum sativum* L., trocas gasosas, fluorescência da clorofila a

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Introduction

Coriander (*Coriandrum sativum* L.) is a vegetable with high demand for consumption worldwide (Prachayasittikul et al., 2017), mainly in the Northeastern region of Brazil, having wide use in cooking (Menezes et al., 2020). Faced with water limitations, especially in arid and semi-arid regions, the use of brackish water can be an alternative to enable the practice of agriculture, and in this context, studies that have evaluated the viability of using the available brackish waters in the cultivation of leafy vegetables, have already been carried out (Campos Júnior et al., 2018; Martins et al., 2020), but with a focus on management techniques.

However, the brackish waters from different regions of the Brazilian northeast exhibit great variations in terms of salt concentration, proportion, and predominance of cations and anions in solution (Silva Júnior et al., 1999), leading to different chemical reactions when the nutrient solution is being prepared, and results in ionic imbalance. On the other hand, in hydroponic systems, the energy reorganization resulting from the minimization of the matric potential stimulates the use of brackish waters and the analysis of the impact of the most relevant cationic prevalence on photochemical efficiency and coriander production.

Analysis of chlorophyll fluorescence, CO_2 internal concentration, instantaneous carboxylation efficiency, and CO_2 assimilation rate helps to understand the limitations imposed by salinity on gas exchange (Shoukat et al., 2019) and on the photosynthetic process (Martins et al., 2019).

Therefore, the present study aimed to evaluate the photochemical efficiency and production of the coriander crop, cultivar 'Verdão', as a function of the electrical conductivity levels of the nutrient solution and the cationic nature.

Material and Methods

The experiment was carried out between November and December 2019 in a greenhouse - arch type, at the Experimental Laboratory for Fertigation and Salinity of the Agricultural Engineering Department - UFRPE, Recife, PE (8° 1'7" S, 34° 56'53" W and 6.5 m altitude).

Within the experimental environment, the data of mean, maximum, and minimum values for the relative humidity of air and temperature were measured with a digital thermo-hygrometer during the study period. Reference evapotranspiration was also monitored by the Penman-Piché method (Figure 1).

The experimental design was in randomized blocks, in a 4 × 3 factorial arrangement, with four replicates. The treatments consisted of exposing the plants to four electrical conductivities of the nutrient solutions (ECns = 1.6, 3.2, 4.8, and 6.4 dS m^{-1}) and three kinds of water of different cationic natures (Na^+; Ca^{2+}; Mg^{2+}), which were prepared in saline waters obtained with the solubilization of different salts - NaCl, $CaCl_2.2H_2O$, and $MgCl_2.6H_2O$ in supply water (ECw = 0.12 dS m^{-1}), that is, three predominant cationic natures.

Each experimental block consisted of a hydroponic structure, made of wooden support, waterproofed with oil

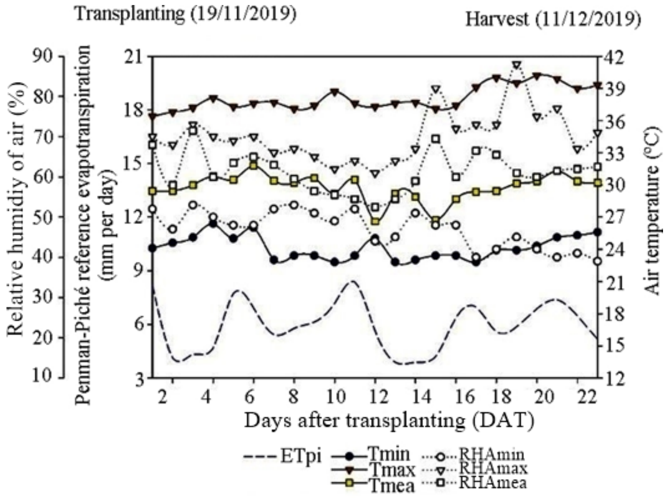


Figure 1. Penman-Piché reference evapotranspiration, relative humidity of air, and temperature inside the greenhouse, during the experimental period

paint; of 2 × 1.40 m dimensions, designed with a support capacity for 2-m-long and 100-mm-diameter PVC tubes (Santos Júnior et al., 2016), each tube representing an experimental plot.

In the tubes, circular "cells" of 60 mm diameter were drilled, spaced equidistantly by 14 cm, considering the central axis of each cell. Joints of the same gauge were attached to the pipes and connected to a valve for water outlet, in a "spillway type" system to induce the formation of a constant 0.04-m-deep nutrient solution film inside the tube, throughout its length, making the solution equally available to all plants.

For the preparation of the brackish waters, the amount of the respective salts, as per treatment, was estimated according to Richards (1954), which were dissolved in 20 L of UFRPE's supply water (ECw = 0.12 dS m^{-1}). The treatments based on NaCl, $CaCl_2.2H_2O$, and $MgCl_2.6H_2O$ had concentrations of respectively 0, 20.30, 40.60, and 60.90; 0, 9.23,18.45, and 27.68, and 0, 10.75, 21.51, and 32.26 $mmol_c$ L^{-1} corresponding to electrical conductivity of the brackish waters of 0.12, 1.72, 3.32, and 4.92 dS m^{-1} for the three cationic nature tested.

Once the brackish waters were prepared, the same amounts of fertilizers were added to each solution to prepare the nutrient solution, only once and at the beginning of the experiment, as follows: 15.0 g of calcium nitrate (15.5% N and 18.0% Ca); 10.0 g of potassium nitrate (12.0% N and 45.0% K); 3.0 g of monoammonium phosphate (12.0% N and 51% P) and, 8.0 g of a commercial product, the Mix of Timac®, which contains magnesium sulfate (11.0% S and 9.0% Mg) + micronutrients (0.5% B, 0.5% Cu, 2.5% Fe, 2% Mn, 0.2% Mo, and 1.5% Zn).

This supply of fertilizers promoted a nutrient solution with the following concentrations of nutrients in mmol L^{-1}: 13.59 of N, 2.37 of Ca, 5.50 of K, 2.61 of P, 1.37 of S, 1.48 of Mg, and in μmol L^{-1}: 180 of B; 30 of Cu; 180 of Fe; 140 of Mn; 8 of Mo; 90 of Zn, corresponding to the electrical conductivity of 1.48 dS m^{-1}. The solutions obtained had electrical conductivities (ECns) of 1.6, 3.2, 4.8, and 6.4 dS m^{-1} in all tested cationic nature.

Coriander (*Coriandrum sativum* L.) cultivar 'Verdão' was used for this study. Sowing was carried out in plastic cups (180 mL) with small holes at the bottom and on all sides, using coconut fiber as a substrate. Fifteen seeds were placed per cup to guarantee germination. Moisture was maintained by spraying 100 mL of supply water twice a day on the seedlings until transplanting to the hydroponic system, which was carried out seven days after sowing (DAS).

After transplanting, the nutrient solution management began, which was characterized by two daily applications - in the morning (8:00 a.m.) and in the afternoon (4:00 p.m.), of 8 L of nutrient solution to the tubes. However, as a closed system was used, the excess of the solution in relation to the level inside the tube returned to the reservoir through a tube.

As water consumption of the plants increased and reduced the volume of solution in the reservoir, every seven days new solution was prepared with the respective brackish water. The values of electrical conductivity (ECns), pH (pHns), dissolved oxygen (DOns), and temperature (Tns °C) of the nutrient solution were monitored daily. There were no phytosanitary problems during the experiment.

At 30 days after sowing (DAS) the fluorescence of chlorophyll a was measured in leaves pre-adapted to the dark using leaf clips for 30 min from 8:30 to 9:30 a.m. The analysis was performed on the second healthy and fully expanded upper leaf, with the aid of the FluorPen fluorometer, model FP 100 (Photon Systems Instruments).

The initial (F_0) and the maximum fluorescence (Fm) were measured, and the following indicators were calculated: variable fluorescence (Fv), obtained by the difference between the maximum and initial fluorescence; maximum photochemical efficiency (Fv/F_0); basal quantum yield of non-photochemical processes in PSII (F_0/Fm), and the quantum photochemical efficiency (Fv/Fm). As for the ratios, it was chosen to discuss only Fv/Fm, F_0/Fm, and Fv/F_0, since they are the most representative of the photochemical state of the leaves or even stress indicators.

In the same evaluation periods and times of the determinations of the fluorescence of the chlorophyll a, measurements of gas exchange variables were performed on a healthy and fully expanded leaf of the middle third of each plant, with the aid of a portable Infrared Gas Analyzer (IRGA), model LICOR LI-6400, in the PAR range of irradiation of 1500 μmol photons m^{-2} s^{-1} and airflow of 200 mL min^{-1}. The variables analyzed were the internal CO_2 concentration (Ci, mmol CO_2 m^{-2} s^{-1}), CO_2 assimilation rate (A, μmol $CO_2 m^{-2}$ s^{-1}), instantaneous carboxylation efficiency (CEi, μmol m^{-2} s^{-1} (μmol $mol^{-1})^{-1}$, stomatal conductance (gs – mmol H_2O m^{-2} s^{-1}), and transpiration (E – mmol H_2O m^{-2} s^{-1}).

In addition, at 30 DAS, harvesting was carried out and shoot fresh mass (SFM) was measured on a precision scale. Then, the samples were placed in Kraft paper bags and dried in a forced-air circulation oven at 60 °C until reaching constant weight to obtain shoot dry mass (SDM). The percentage of SDM (%SDM) was then calculated.

The data obtained were analyzed in the statistical package SISVAR, being subjected to analysis of variance by the F test at the 0.05 probability level ($p \leq 0.05$). If significant effects were found, the electrical conductivities of the nutrient solution were analyzed through regression analysis (quantitative factors) and the cationic nature of water (qualitative factors) using the means comparison test (Tukey ($p \leq 0.05$)).

Results and Discussion

The replacement of the evapotranspired water volume with the respective brackish water used in the preparation of the nutrient solution caused an increase in the electrical conductivity of the nutrient solution (ECns) throughout the cycle for all cationic natures (Figure 2). The largest increase observed was 14.8% in the ECns of 3.2 dS m^{-1} (Na^+) compared to the initial value, but the treatment with ECns of 6.4 dS m^{-1} and Mg^{2+} cationic nature showed a reduction of 0.5% in ECns (Figure 2A and 2C).

The pH remained within the recommended range for hydroponic cultivation (Furlani, 1999), with values ranging from 6.0 to 7.2 throughout the cycle for all treatments (Figure 2).

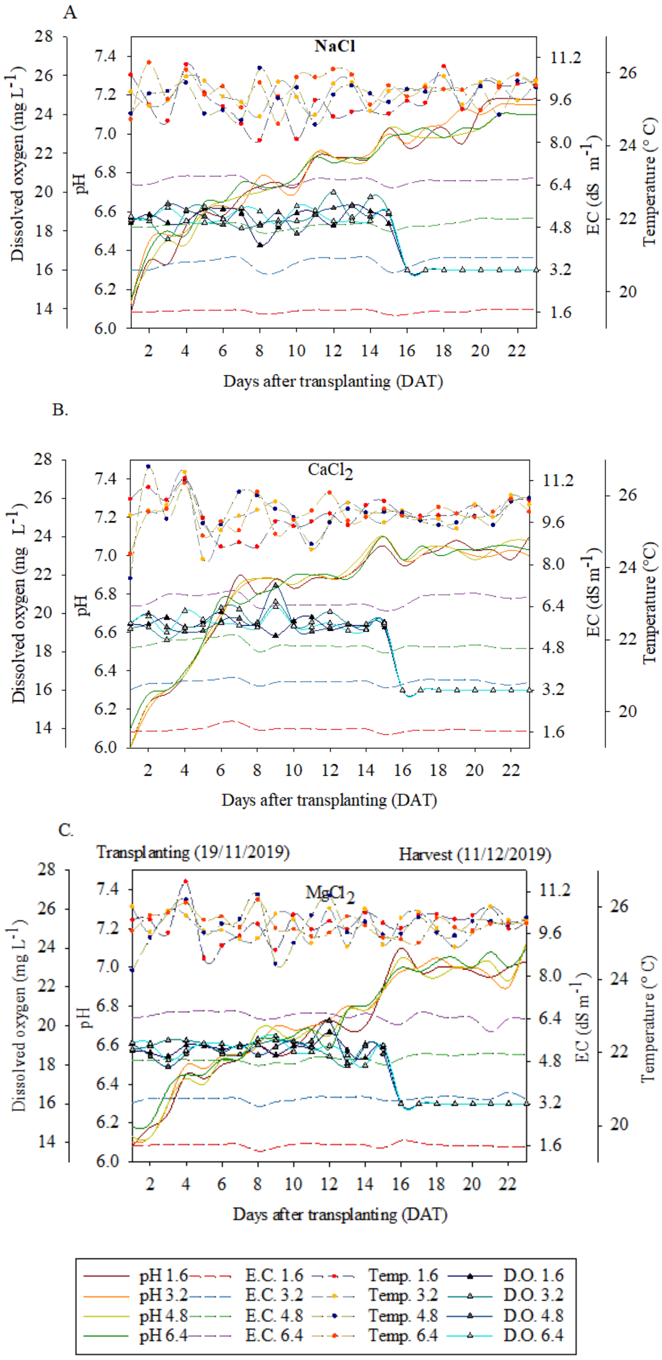


Figure 2. Variation of dissolved oxygen, temperature, pH, and electrical conductivity of nutrient solutions prepared with (A) NaCl, (B) $CaCl_2.2H_2O$, and (C) $MgCl_2.6H_2O$

As for the temperatures of the nutrient solution (Tns °C) prepared with brackish water with Na^+, there was a maximum of 27.7 °C, with an average of 25.4 °C and a minimum of 23.5 °C (Figure 2A), while when using Ca^{2+} the maximum Tns was 27.3 °C, with an average of 25.5 °C, and the minimum of 22.9 °C (Figure 2B). A maximum of 27.6 °C, an average of 25.5 °C, and a minimum of 23.4 °C were observed when Mg^{2+} was used (Figure 2C). In general, it is inferred that all treatments obtained similar mean and minimum temperature values; corroborating the results, Bremenkamp et al. (2012) comment that within the range from 24 to 27 °C, the temperature of the nutrient solution does not cause significant differences in plant growth.

The oxygen dissolved in the nutrient solution (Figures 2A, B, and C) initially ranged from 18 to 20 ppm for all treatments, with a reduction and stabilization to 16 ppm from 16 DAT until harvest. Nevertheless, Silva et al. (2015b) obtained average concentrations of 6.1 and 6.3 ppm in the morning and afternoon periods, respectively, in the cultivation of hydroponic coriander.

The interaction between the sources of variation influenced ($p \leq 0.05$) the initial fluorescence – F_0, the maximum efficiency of the photochemical process in the PSII – Fv/F_0, the basal quantum yield of the non-photochemical processes in the PSII –F_0/Fm, and the maximum quantum yield - Fv/Fm. Maximum fluorescence - Fm and variable fluorescence - Fv were affected ($p \leq 0.05$) exclusively by the electrical conductivity of the nutrient solution (Table 1).

In waters with a predominance of Na^+, F_0 was minimal (5544.82) under an ECns of 5.38 dS m^{-1}. It was also minimal (5769.10) under an ECns of 5.86 dS m^{-1} when there was a prevalence of Ca^{2+}, and when there was a greater amount of Mg^{2+} in water, the minimum initial fluorescence (4982.3) was estimated for the ECns of 6.4 dS m^{-1} (Figure 3A). On the other hand, when comparing the cationic prevalence at each ECns, there were differences ($p \leq 0.01$) under 3.2 (Ca^{2+}=Mg^{2+}>Na^+), 4.8 (Ca^{2+}=Na^+> Mg^{2+}), and 6.4 dS m^{-1} (Ca^{2+}=Na^+> Mg^{2+}) (Figure 3A).

In leafy vegetables such as parsley, Martins et al. (2020) found a reduction in F_0 with increasing salinity, which indicates that the reduction in leaf water potential induced by salinity may have resulted in damage to the reaction center of photosystem II or reduced ability to transfer the excitation energy of the light-harvesting system to the reaction center. On the contrary, Oliveira et al. (2018) observed an increase in F_0 when cotton plants were exposed to salinity. This difference in results can be attributed to the difference in salinity tolerance of the crops.

The Fm was affected ($p \leq 0.05$) in a relative way by the increase in the concentration of salts, being minimal (28047.16) at the estimated ECns of 4.53 dS m^{-1} (Figure 3B). The peak of fluorescence (Fm) occurs when the quinone A - QA (primary electron receptor of quinone of the PSII) is reduced and the reaction centers are unable to increase photochemical reactions, reaching their maximum capacity (Baker & Rosenqvst, 2004).

The increase in the concentration of salts in the nutrient solution possibly implied the inactivation of PSII in the thylakoid membranes, a fact that imposes deficiencies in the photoreduction process of quinone A. With the electron flow between the photosystems compromised, the photochemical activity in the leaves also becomes limited, implying damage to the plant's ability to transfer energy in order to form NADPH reducer, ATP, and reduced ferredoxin, thus limiting the CO_2 assimilation capacity in the biochemical phase of photosynthesis (Baker, 2008).

The variable fluorescence (Fv) was increased by 395.96 for each increment in dS m^{-1}. In plants exposed to the ECns of 6.4 dS m^{-1}, the estimated Fv was 23308.4, which represented a gain of 8.8% when compared to the Fv of plants under the ECns of 1.6 dS m^{-1} (Figure 3C).

The increase in Fv values is related to a greater capacity for CO_2 assimilation in the biochemical phase of photosynthesis. Under saline conditions, some authors (Lima et al., 2019) reported an increase in Fv due to nitrogen fertilization, especially when the main source is nitrate, as is the case here, which can be attributed to the importance of this element in the synthesis of organic compounds, such as chlorophyll and in the composition of several biomolecules and countless enzymes, essential for increasing the osmotic adjustment capacity, in addition to being necessary for the maintenance of photosynthetic capacity.

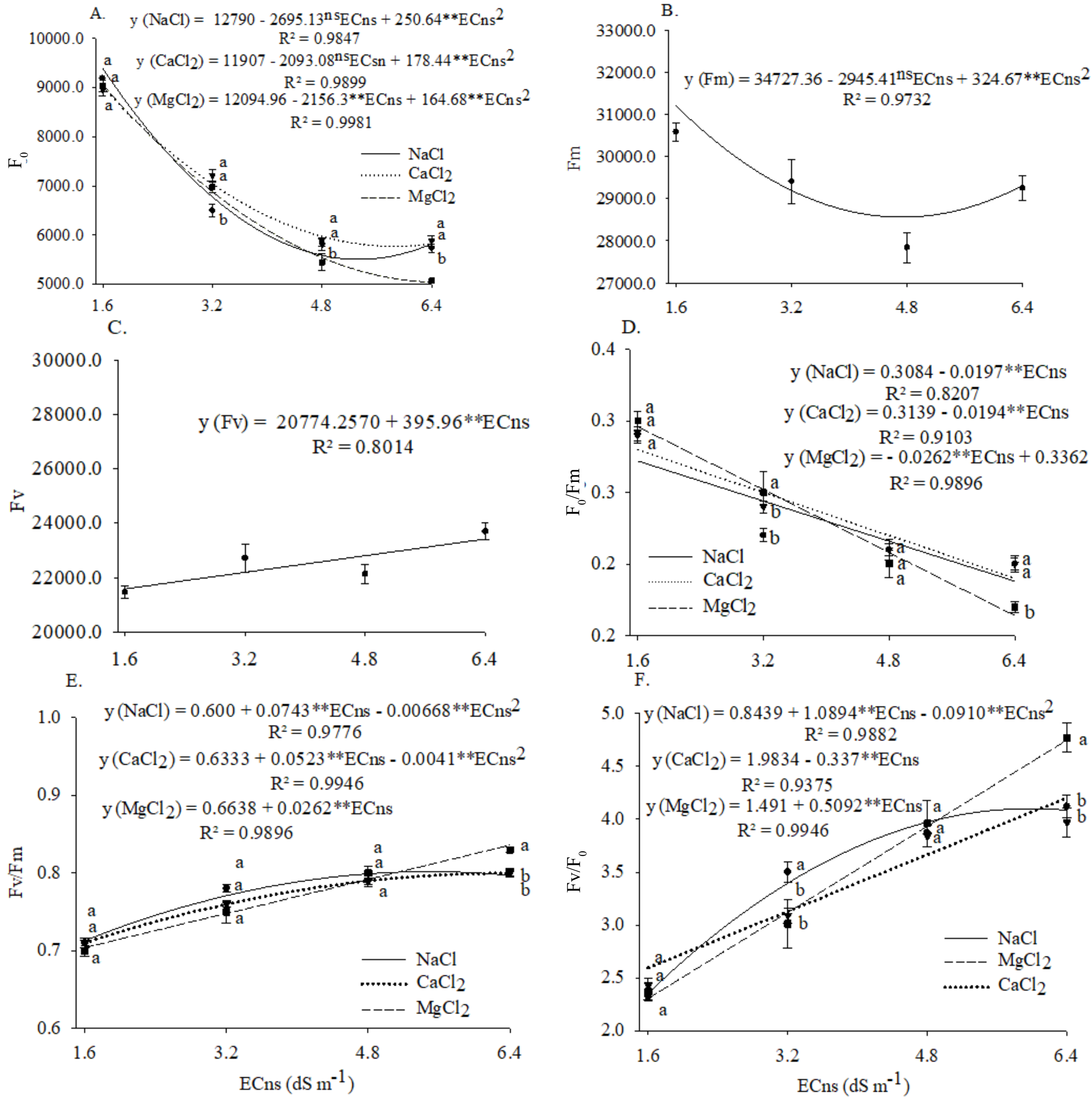
The basal quantum yield of non-photochemical processes in PSII (F_0/Fm) was reduced ($p \leq 0.05$) at a rate of 0.0197, 0.0194, and 0.0262 for each dS m^{-1} increase when there was a prevalence of Na^+, Ca^{2+}, and Mg^{2+}, respectively (Figure 3D).

As for cationic nature, it was found that as the salt concentration increased (ECns = 6.4 dS m^{-1}), the F_0/Fm ratio in plants exposed to the prevalence of Na^+ and Ca^{2+} was higher

Table 1. Analysis of variance for initial (F_0), maximum (Fm), and variable (Fv) fluorescence; for the basal quantum yield of non-photochemical processes in PSII (F_0/Fm), for maximum quantum yield (Fv/Fm), and for the maximum efficiency of the photochemical process in PSII (Fv/F_0) in coriander plants exposed to nutrient solutions prepared in water with different electrical conductivities (ECns) and cationic nature (CN)

Source of variation	DF	Mean square					
		F_0	Fm	Fv	F_0/Fm	Fv/Fm	Fv/F_0
ECns	3	$3.1 \times 10^{7**}$	$1.8 \times 10^{7**}$	$1.0 \times 10^{7**}$	0.026^{**}	0.03^{**}	8.48^{**}
Linear Regression	1	$8.2 \times 10^{7**}$	$1.9 \times 10^{7**}$	$2.4 \times 10^{7**}$	1.9×10^{-4ns}	0.07^{**}	24.88^{**}
Quadratic Regression	1	$1.2 \times 10^{7**}$	$3.3 \times 10^{7**}$	$4.5 \times 10^{7**}$	0.0006^{*}	0.005^{**}	0.56^{**}
CN	2	$4.4 \times 10^{5**}$	3.8×10^{6ns}	1.9×10^{6ns}	0.0004^{ns}	1.3×10^{-4ns}	0.16^{ns}
ECns × CN	6	$3.6 \times 10^{7**}$	7.7×10^{5ns}	1.3×10^{5ns}	0.0002^{**}	$5.9 \times 10^{-4**}$	0.29^{**}
Blocks	3	6.0×10^{4ns}	3.4×10^{6ns}	3.9×10^{6ns}	4.0×10^{-4ns}	4.1×10^{-4ns}	0.19^{*}
Residual	33	4.7×10^{4ns}	1.5×10^{6}	1.5×10^{7}	1.7×10^{-4}	1.7×10^{-4}	0.06
CV (%)		3.19	4.16	5.55	5.58	1.69	7.22

CV - Coefficient of variation; DF - Degree of freedom; * and ** Respectively not significant, significant at $p \leq 0.05$ and $p \leq 0.01$ by F test



Vertical bars represent the standard error of the mean (n = 4). Means followed by the same letters indicate no significant difference between treatments by the Tukey test ($p \leq 0.05$) with respect to the cationic nature at the same electrical conductivity of the nutrient solution

Figure 3. Initial fluorescence – F_0 (A), maximum fluorescence - Fm (B), variable fluorescence - Fv (C), and basal quantum yield of non-photochemical processes in PSII - F_0/Fm (D), maximum quantum yield - Fv/Fm (E), and maximum efficiency of the photochemical process in PSII - Fv/F_0 (F) in coriander plants exposed to nutrient solutions prepared in water with different electrical conductivities and cationic nature

($p \leq 0.05$) than in plants under the prevalence of Mg^{+2} (Figure 3D). In the present study, the values of F_0/Fm, for the most part, were within the range from 0.14 to 0.20, considered normal (Roháček, 2002).

In the current study, under the prevalence of Na^+ and Ca^{2+}, the Fv/Fm ratio was maximal (0.8) at the estimated ECns of 5.56 and 6.37 dS m^{-1}, respectively. However, the gain estimated for each dS m^{-1} increase in ECns was approximately 0.0262, under the prevalence of Mg^{2+} in water (Figure 3E).

Regarding the cationic nature, significance ($p \leq 0.05$) was only found when there was a prevalence of Mg^{2+} at the level of 6.4 dS m^{-1}. According to Reis & Campostrini (2011), when the photosynthetic apparatus is intact, the values of Fv/Fm vary between 0.75 and 0.85, that is, in the present study, in most cases, there was no inhibition in the quantum efficiency of PSII, nor photoinhibitory damage in the PSII reaction centers.

Although the Fv/F_0 ratio contains the same basic information, its discussion amplifies the small variations detected by the Fv/Fm ratio, so the Fv/F_0 ratio may be used to detect changes induced by stress (Lotfi et al., 2020).

When there was a prevalence of Na^+, the Fv/F_0 ratio was maximal (4.10) at the estimated ECns of 5.98 dS m^{-1} and, under Ca^{2+} and Mg^{2+}, the decrease in the Fv/F_0 ratio for each increment in dS m^{-1} was estimated at 0.337 and 0.5092, respectively (Figure 3F).

When comparing the cationic prevalence at each ECns, there was significance, at ECns of 3.2 and 6.4 dS m^{-1}, and better performance of Na^+ and Mg^{2+} compared to the others. In the present study, at the lowest levels of ECns (1.6 and 3.2 dS m^{-1}), values below 4.0 (Figure 3F) were observed; however, at the highest levels of ECns, the values of Fv/F_0 were within the range between 4.0 and 6.0, considered adequate for plants grown under ideal conditions (Silva et al., 2015a).

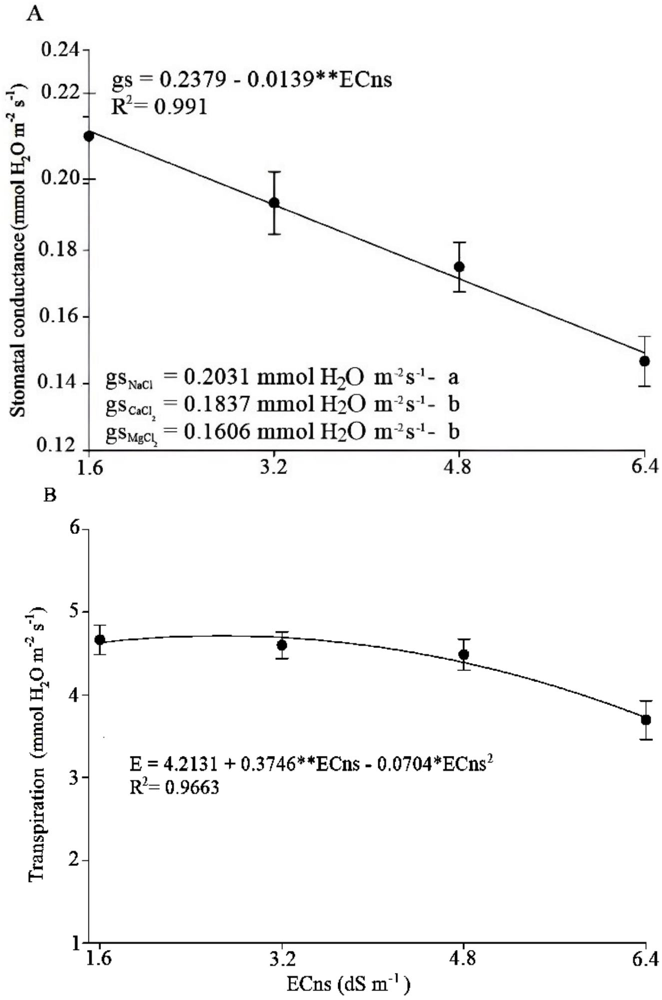
On the other hand, Martins et al. (2020), when exposing parsley plants to nutrient solutions prepared in brackish waters with a prevalence of Na^+, found that the Fv/F_0 ratio was maximal (3.18) at the estimated ECns of 5.49 dS m^{-1}. Although the same trend was verified in the present study, the difference between the maximum values can be attributed to the asymmetry in the tolerance of the crops and the difference in management practices adopted.

Except for shoot dry mass (SDM), which was influenced ($p \leq 0.05$) by the sources of variation individually, all other variables were affected ($p \leq 0.05$) by the interaction between ECns and the cationic nature tested.

The gs was reduced at a rate of 5.84% for each increment in dS m^{-1}, totaling a reduction of 31.52% within the range of ECns studied (Figure 4A). On the other hand, there were more significant results ($p \leq 0.01$) in gs when the plants were exposed to water with a prevalence of $Na^+ > Ca^{2+} > Mg^{2+}$ (Figure 4A). The transpiration was maximal (4.71 mmol H_2O m^{-2} s^{-1}) at the estimated ECns of 2.66 dS m^{-1} (Figure 4B).

The decrease in gs as a function of the increase in concentration can be understood as a mechanism of plant tolerance to salinity, that is, in plants under ECns greater than 2.66 dS m^{-1} there was a tendency to reduce transpiration, which can be attributed to the increase in osmotic demand and, consequently, the reduction in water flow in the plant. The reduction in gs and E verified in the present study was also verified by other authors (Guimarães et al., 2019; Cavalcante et al., 2019).

The internal CO_2 concentration was minimal (188.76 mmol CO_2 m^{-2} s^{-1}) at the estimated ECns of 3.41 dS m^{-1} and, for each dS m^{-1} increment, increases in Ci around 14.715 and 4.77 mmol CO_2 m^{-2} s^{-1} were estimated when the solutions were prepared with salts of Ca^{2+} and Mg^{2+} in the water, respectively (Figure 5A).



Vertical bars represent the standard error of the mean (n = 4). Means followed by the same letters indicate no significant difference between treatments with respect to cationic nature by the Tukey test ($p \leq 0.05$)

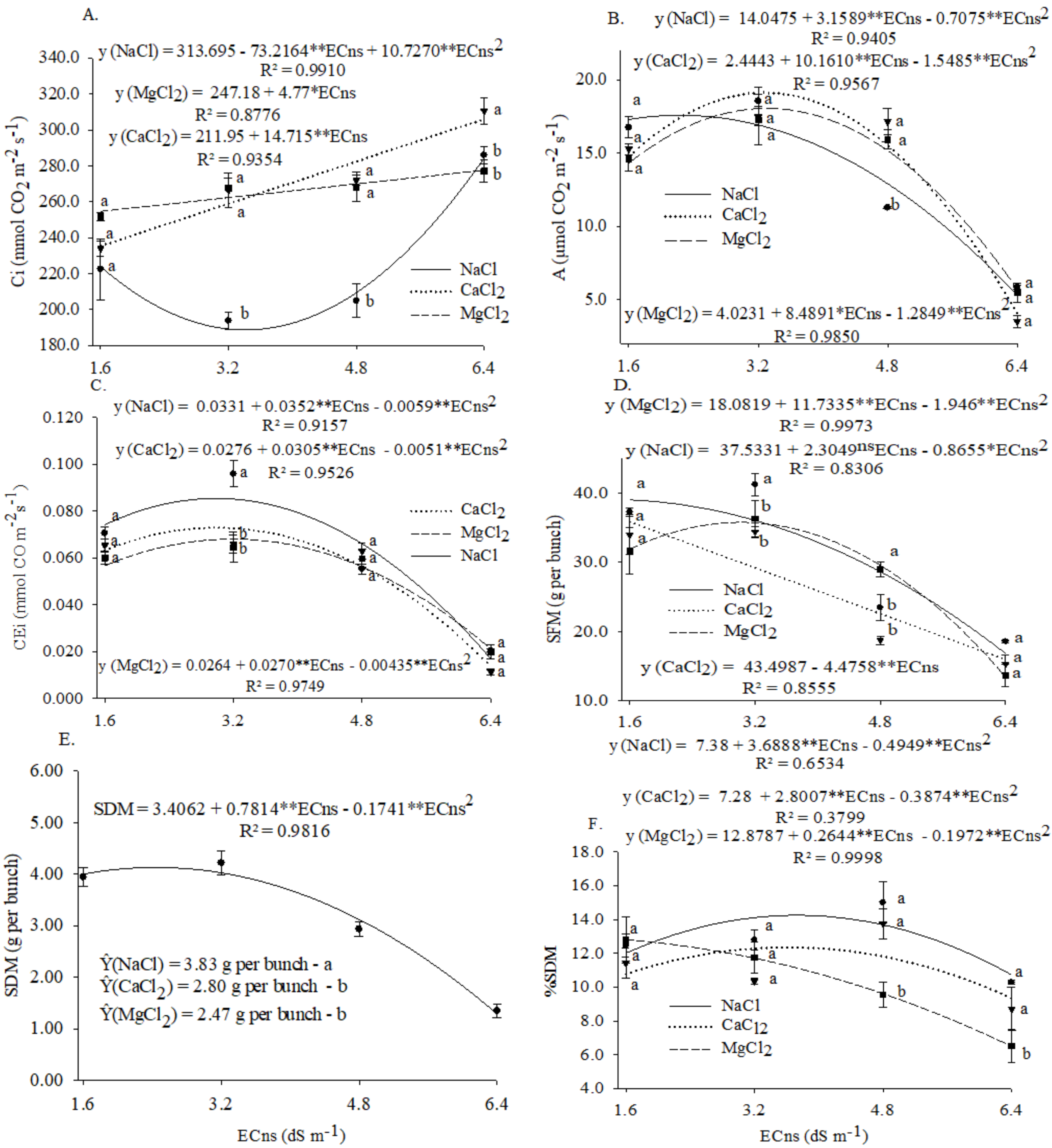
Figure 4. Stomatal conductance (A) and transpiration (B) in coriander plants exposed to nutrient solutions prepared in water with different electrical conductivities and cationic nature

With the increase in ECns, the effect of different cations on Ci was more pronounced under ECns of 3.2 and 4.8 dS m^{-1} and, at ECns of 6.4 dS m^{-1}, Ci under Ca^{+2} prevalence in water was higher ($p \leq 0.05$) compared to the other cations. On the other hand, according to Tatagiba et al. (2014), the increase in Ci induced by salinity can be attributed to the decrease in stomatal conductance (gs), transpiration (E), and CO_2 assimilation rate (A).

Table 2. Analysis of variance of stomatal conductance (gs), transpiration (E), internal CO_2 concentration (Ci), CO_2 assimilation rate (A), instantaneous carboxylation efficiency (CEi), shoot fresh (SFM) and dry mass (SDM) and shoot dry mass percentage (%SDM) in coriander plants exposed to nutrient solutions prepared in water with different electrical conductivities (ECns) and cationic nature (CN)

Source of variation	DF	Mean square							
		gs	E	Ci	A	CEi	SFM	SDM	%SDM
ECns	3	0.0099^{**}	2.42^{**}	7461.74^{**}	388.39^{**}	$8.0 \times 10^{-3**}$	1168.26^{**}	27.76^{**}	43.95^{**}
Linear Regression	1	0.0295^{**}	5.46^{**}	725.20^{**}	320.32^{**}	0.016^{**}	2853.08^{**}	57.49^{**}	3.74^{ns}
Quadratic Regression	1	0.0002^{ns}	1.56^{*}	438.26^{**}	52.49^{**}	0.008^{**}	355.34^{**}	9.54^{**}	25.68^{**}
CN	2	0.0072^{**}	0.44^{ns}	9377.90^{**}	0.297^{ns}	$4.6 \times 10^{-4**}$	82.69^{**}	4.95^{**}	25.32^{**}
ECns × CN	6	0.0012^{ns}	$0,22^{ns}$	1851.98^{**}	0.30^{**}	$3.6 \times 10^{-4**}$	42.84^{**}	0.32^{ns}	9.85^{*}
Blocks	3	0.0020^{*}	2.56^{**}	63.73^{ns}	1.92^{ns}	4.1×10^{-5ns}	29.28^{ns}	0.10^{ns}	5.84^{ns}
Residual	33	0.0006	0.29	259.63	256	5.0×10^{-5}	11.78	0.14	3.01
CV (%)		13.54	12.41	6.33	12.41	12.05	13.00	12.35	11.64

CV - Coefficient of variation; DF - Degree of freedom; * and ** Respectively not significant, significant at $p \leq 0.05$ and $p \leq 0.01$ by F test



Vertical bars represent the standard error of the mean (n = 4). Means followed by the same letters do not differ by the Tukey test (p ≤ 0.05) with respect to the cationic nature at the same electrical conductivity of the nutrient solution

Figure 5. Internal CO_2 concentration (A), CO_2 assimilation rate (B), instantaneous carboxylation efficiency (C), shoot fresh (D) and dry mass (E), and percentage of shoot dry mass (F) in coriander plants exposed to nutrient solutions prepared in water with different electrical conductivities and cationic nature

When there is an accumulation of CO_2 in the leaf mesophyll, this may indicate that CO_2 is not being used for the synthesis of sugars by the photosynthetic process, with the accumulation of this gas, indicating that some non-stomatal factor is interfering with this process, resulting in increased resistance to the diffusion of CO_2 to the substomatal chamber (Freire et al., 2014).

The CO_2 assimilation rate (A) was maximal (17.57, 19.11, and 18.04 μmol CO_2 m^{-2} s^{-1}) at the estimated ECns of 2.23, 3.28, and 3.30 dS m^{-1}, when there was prevalence of Na^+, Ca^{2+}, and Mg^{2+} respectively (Figure 5B). Availability of water to plants is one of the fundamental factors for photosynthesis (Silva et al., 2015a), and its limitation, common in situations of salt stress, triggers a series of adjustments and affects the CO_2 assimilation rate (Silva et al., 2013; Taiz & Zeiger, 2017), thus, the observed increase in the internal concentration of CO_2 may be associated with the reduction verified in the CO_2 assimilation rate (A), which implies the reduction of carboxylation rate and the consequent accumulation of CO_2.

The instantaneous carboxylation efficiency (CEi) is associated with the availability of ATP and NADPH and the RuBisCO substrate for plants, with higher concentrations of CO_2, as well as the amount of light, temperature, and ideal conditions for enzymatic activity, are preponderant factors for high instantaneous carboxylation efficiency (Silva et al., 2015a). In the present study, the CEi was maximal (0.086, 0.073, and 0.068 μmol m^{-2} s^{-1} (μmol mol^{-1})$^{-1}$) at the estimated ECns of 2.98, 2.99, and 3.10 dS m^{-1} when the water used in the preparation of the nutrient solution had a prevalence of Na^+, Ca^{2+}, and Mg^{2+}, respectively (Figure 5C).

The CO_2 assimilation rate (A) and the instantaneous carboxylation efficiency (CEi) did not differ ($p > 0.05$) due to the cationic nature as concentration increased (6.4 dS m^{-1}). As a result of the increase in the internal concentration of CO_2 (Figure 5A) even with the increase in ECns, in all cationic natures, there was a reduction in the carboxylation efficiency (CEi) of the plants, that is, the increase in the concentration of salts in the nutrient solution caused a reduction in the carboxylation rate (Figure 5C).

It is evident, therefore, that the limitation in CO_2 assimilation rate (A) (Figure 5B), verified in plants as the ECns increased, is related not only to stomatal factors but, above all, to non-stomatal aspects. Taiz & Zeiger (2017) comment that the non-stomatal effect is related to changes caused by the various photochemical processes, such as reduction in electron transport, affecting the formation of ATP and NADPH, and in the biochemical processes with the reduction in carboxylation efficiency and/or quantity and activity of RuBisCO and other enzymes of photosynthetic metabolism.

The damage is seen in the reaction centers and the limitations in A, CEi, and in the entire photosynthetic process already discussed, evidently had negative effects on the biomass production of the plants (Silva et al., 2013).

When there was a prevalence of Na^+ and Mg^{2+} in the water, SFM was maximal (39.00 and 35.768 g $bunch^{-1}$) at estimated ECns of 1.60 and 3.01 dS m^{-1}, respectively (Figure 5 D). However, with each increment of dS m^{-1}, SFM decreased by 4.475 g $bunch^{-1}$ when there was a prevalence of Ca^{2+}. With the increase in concentration (ECw = 3.2 and 4.8 dS m^{-1}), there were differences ($p \leq 0.05$) between the SFM of plants exposed to the solutions with predominance of Na^+ and Mg^{2+} compared to those with Ca^{2+}.

Gains in the production of fresh and dry biomass in coriander plants with the increase in the concentration of salts were also verified by Martins et al. (2019), who also found that the prevalence of Na^+, Ca^{2+}, and Mg^{2+} impacts differently ($p \leq 0.05$) the SFM of parsley with increasing concentration.

SDM was maximal (4.28 g per bunch)at the estimated ECns of 2.24 dS m^{-1}, and the results obtained under the prevalence of $Na^+ > Ca^{2+} = Mg^{+2}$ stood out ($p \leq 0.05$). The SDM observed in plants with a prevalence of Na^+ was up to 1.55 times higher than those observed in plants exposed to a higher concentration of Mg^{+2} (Figure 5E).

The damage associated with the osmotic effect due to the increase in the salt concentration was also verified in the SDM of coriander by Santos et al. (2019) and also in the SFM and SDM of different leafy vegetables (Campos Júnior et al., 2018; Santos et al., 2019; Martins et al., 2020).

The effects of the ionic component on the intensity of the damage to the PSII reaction center associated with minimization of the carboxylation efficiency and CO_2 assimilation rate verified in the production of fresh and dry biomass, also reflected in the %SDM, as characterized by visual symptoms of toxicity.

The %SDM was maximal (14.25, 12.34, and 12.79%) at the estimated ECns of 3.72, 3.61, and 1.6 dS m^{-1}, respectively, with the increase in salt concentration in the nutrient solution. The effect of the different and predominant cations became more evident ($p \leq 0.05$) in the order $Na^+=Ca^{2+}>Mg^{2+}$ when analyzing the cationic prevalence at the ECns of 4.8 and 6.2 dS m^{-1} (Figure 5F).

Conclusions

1. The increase in the electrical conductivity of the nutrient solution affected reaction centers, photochemical activity, and carboxylation efficiency and resulted in reductions in stomatal conductance, CO_2 assimilation rate, and therefore, in the biomass production of coriander.

2. Cationic prevalence in water causes differences in the intensity of salt damage, especially with increasing concentration with an emphasis on the SDM of plants exposed to the prevalence of $Na^+ > Ca^{2+} = Mg^{2+}$.

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