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ORIGINAL PAPER

Plant density to compensate for coriander production losses caused by the isolated and/or combined effects of salt and root-zone temperature stresses

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Abstract: Hydroponics has represented an emergent solution for arid and semi-arid regions due to freshwater limitations, especially for promoting better plant growing conditions using brackish waters. Besides salt stress, the plants are exposed to other abiotic stresses, such as temperature, which may further enhance the salinity effect. Given the above, two experiments were conducted with coriander grown at different plant densities using an NFT (nutrient film technique) hydroponic system. The first experiment occurred from January to February by submitting plants to saline water produced with salts of different cationic natures, and the second was from October to November using the same water (only NaCl) combined with different root-zone temperatures (RZTs), both in 2021. Experiment I included the control (electrical conductivity of water – ECw of 0.25 dS m^{-1}) and six other treatments with ECw of 6.50 dS m^{-1} obtained by dissolving NaCl, KCl, $MgCl_2$, $CaCl_2$, NaCl + $CaCl_2$ + $MgCl_2$, and NaCl + $CaCl_2$ + KCl. Experiment II combined two ECw levels (0.25 and 6.50 dS m^{-1}) with three RZTs (ambient – ARZT, ARZT + 2°C, and ARZT + 4°C, corresponding to the mean values of 28.80, 30.64, and 32.59°C). Both experiments distributed five plant densities (6, 12, 18, 24, and 30 plants $bunch^{-1}$) in subplots in the hydroponic channel (main plot). Using water with a high salinity level (ECw 6.50 dS m^{-1} with salts of different cationic natures) allowed coriander cultivation, except for $MgCl_2$, which led to higher production losses. Higher number of plants (density of 30 plants) compensated for production losses due to the stress, with yields comparable to those without salt stress at the lowest density of 6 plants. Experiment II partially confirmed this compensation, provided RZT would not exceed 30.64°C when using saline water (ECw 6.50 dS m^{-1}) for production.

Keywords: *Coriandrum sativum* L., water availability, abiotic stresses, cationic nature.

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Introduction

Rainfall varies widely in arid and semi-arid regions, causing water deficit for most of the year (Marengo et al., 2018; Freitas et al., 2022; Lessa et al., 2023a), and climate change effects further aggravate this condition (Panahi et al., 2021). Therefore, food security for more vulnerable communities in these regions comes under pressure during drought periods because small-scale farmers practice subsistence agriculture, depending on rainfall to ensure agricultural production (Alvalá et al., 2019; Meza et al., 2021).

Brackish waters from tube wells are essential to more vulnerable communities of arid and semi-arid regions due to the scarcity of surface freshwater (Silva et al., 2020a; Lessa et al., 2023b; Silva et al., 2023ab); therefore, these waters have often been used to irrigate crops (Silva et al., 2021a; Cavalcante et al., 2022). However, this practice may increase the risk of soil salinization, depreciating cultivated areas and reducing crop yield expectations (Bione et al., 2021; Rahman et al., 2021; Venâncio et al., 2022).

Several strategies have been applied to mitigate the adverse effects of salinity stress on plants caused by salts in the soil and/or irrigation water (Al-Garni et al., 2019; Atzori et al., 2019; Omar et al., 2023). Hydroponics (cultivation without soil) has represented an alternative to traditional soil cultivation among different strategies (Bione et al., 2021; Germano et al., 2022; Silva et al., 2023ab). It allows for cultivating several plant species using water with high electrical conductivity (ECw) levels (Silva, 2023). Some examples are 7.1 dS m^{-1} in bell pepper (Santos et al., 2018), 6.0 dS m^{-1} in endive (Alves et al., 2019), 5.5 dS m^{-1} in cauliflower (Costa et al., 2020; Silva et al., 2023c), 4.6 dS m^{-1} in watercress (Souza et al., 2020a), 7.5 dS m^{-1} in green onion (Souza et al., 2020b), 4.0 dS m^{-1} in mini watermelon (Ó et al., 2022), and 6.5 dS m^{-1} in Biquinho pepper (Bione et al., 2021) and rocket (Silva et al., 2022). Such values refer only to ECw levels and become even higher after adding nutrient salts.

Saline levels were artificially obtained using sodium chloride (NaCl) for the experimental purposes of the mentioned studies. However, naturally exploited groundwater in many arid and semi-arid regions (Ahmadi and Souri, 2018; Chang et al., 2022), such as the Brazilian Northeast, contain other salts of different cationic natures, namely calcium – Ca, magnesium – Mg, and potassium – K (Cruz et al., 2021; Santos Júnior et al., 2021). Other studies under hydroponic conditions had brackish waters produced from $MgCl_2$, $CaCl_2$, or KCl salts individually (Lira et al., 2019; Martins et al., 2019a; Bezerra et al., 2022; Muchecua et al., 2022) or by mixing NaCl + $CaCl_2$ + $MgCl_2$ salts in an equivalent 7:2:1 ratio, respectively (Batista et al., 2021; Dantas et al., 2022; Mendonça et al., 2022; Oliveira et al., 2023a; Soares et al., 2023).

In the present study, the coriander (*Coriandrum sativum* L.) was used. The largest production area in Brazil is concentrated in the northeast region, standing out for hydroponic cultivation (Santos Júnior et al., 2015; Cavalcante et al., 2016; Silva et al., 2016a; Soares et al., 2017; Silva et al., 2018a, Silva et al., 2023de). Fresh coriander biomass is the primary commercialization form for cooking in this region (Silva et al., 2023d) and other countries (Ghazi, 2018; Jamila et al., 2019; Özyazici, 2021). Coriander grown in an nutrient film technique (NFT) hydroponic system using brackish waters received maximum ECw levels of 8.5 dS m^{-1} (Silva et al., 2015), 6.5 dS m^{-1} (Silva et al., 2020b; Silva et al., 2022), and 4.6 dS m^{-1} (Bezerra et al., 2022). The first study used brackish water only to replenish the water consumed by plants, and the others used it exclusively for preparing nutrient solutions and replacing water consumed by plants.

Silva et al. (2021b) and Silva et al. (2023c) state that exclusively using brackish waters considerably increases the electrical conductivity of nutrient solutions (ECsol), especially in the hottest season of the year, due to the higher water demand in the cultivation cycle. Therefore, higher root-zone temperature (RZT) may further potentiate the salinity effect (Maludin et al., 2020; Silva et al., 2020b; Silva et al., 2022). Coriander was also evaluated for the impact of RZT stress alone (Nguyen et al., 2019; Nguyen et al., 2020) or combined with salt stress (Silva et al., 2020b; Silva et al., 2022).

Unlike other leafy vegetables, such as lettuce (a single plant is produced per hole, spaced throughout the hydroponic channel), coriander is produced in bunches, cultivated with a certain number of plants per hole, and sown in cups/containers filled with a coconut fiber substrate (Santos Júnior et al., 2015; Cavalcante et al., 2016; Santos Júnior et al., 2023) and/or in phenolic foam (Soares et al., 2017; Nguyen et al., 2020; Silva et al., 2023d). Hence, increasing the number of plants in the cultivation unit may be strategic to compensate for such coriander production losses when grown under salt and/or RZT stress. Therefore, the present study evaluated coriander cultivation at different plant densities, using saline water produced with salts of different cationic natures (NaCl, KCl, $MgCl_2$, and $CaCl_2$) or with the same water (only with NaCl) combined with RZTs in an NFT hydroponic system.

Materials and Methods

Study site, experimental design, and growth conditions

This study conducted two experiments with coriander under hydroponic conditions in a greenhouse (east-west orientation and uncontrolled conditions with natural sunlight): the first occurred from January to February (Experiment I, summer) and the second from October to November (Experiment II, spring), in 2021. The facilities are part of the experimental area of the Post Graduate Program in Agricultural Engineering of the Federal University of Recôncavo da Bahia (UFRB), Cruz das Almas, Bahia (12° 40’ 19” S, 39° 06’ 23” W, at an elevation of 220 m above sea level), Brazil.

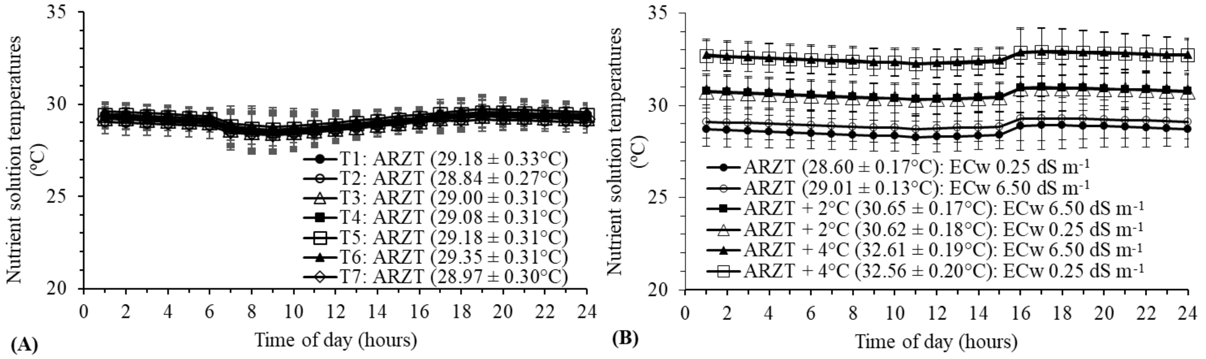
The greenhouse (7.0-m-wide and 24-m-long) had a ceiling height of 2.5 m built with treated eucalyptus wood and a total height with a metallic arch of 4.5 m. The sides of the facility were protected by black screens with 50% shading, and the roof was covered with 150-µm-thick polyethylene transparent film. At the center, a DHT22 (AM2302) sensor was placed 2.0 m above ground level to obtain the air temperature and relative humidity during the crop cycle. The sensor was connected to the Arduino Uno equipped with a data logging shield integrating a real-time clock (RTC) with date, time, and calendar functions. An memory card stored the data, with means recorded every 10 min. All components of the present study were from a Brazilian company (Usina Ind. Comércio e Importação, Santo Ângelo, RS, Brazil), including those used for controlling nutrient solution temperatures for Experiment II. The mean air temperature and relative humidity inside the greenhouse were 29.11 ± 1.49°C and 73.14 ± 9.05% and 27.65 ± 2.63°C and 86.62 ± 6.30% during Experiments I and II, respectively.

A randomized block experimental design was adopted with five and four replications for Experiments I and II, respectively. Experiment I included the control – T1 (electrical conductivity of water – ECw of 0.25 dS m^{-1}) and six other treatments using saline water (ECw of 6.50 dS m^{-1}) produced with salts of different cationic natures (T2 – NaCl, T3 – KCl, T4 – $MgCl_2.6H_2O$, T5 – $CaCl_2.2H_2O$, T6 – NaCl + $CaCl_2.2H_2O$ + $MgCl_2.6H_2O$ in an equivalent 7:2:1 ratio, and T7 – NaCl + $CaCl_2.2H_2O$ + KCl in an equivalent 7:2:1 ratio).

Experiment II combined two ECw levels (0.25 and 6.50 dS m^{-1} with NaCl) with three root-zone temperatures – RZTs (ambient – ARZT, ARZT + 2°C, and ARZT + 4°C). Both experiments used five plant densities (6, 12, 18, 24, and 30 plants $bunch^{-1}$) in subplots distributed in the hydroponic channel. In Experiment I, low-salinity water (ECw 0.25 dS m^{-1}) was used in all treatments for replenishing water consumed by plants. While in Experiment II, the waters (ECw of 0.25 or 6.50 dS m^{-1}, namely low-salinity and brackish) were used for preparing nutrient solutions and replenishing water consumed by plants.

The plants were cultivated in an nutrient film technique (NFT) hydroponic system consisting of 6-m-long channels made of 0.075-m-diameter irrigation PVC tubes. Four hydroponic channels were arranged per bench with a 3.0% slope, maintaining a 0.25 × 0.30 m distance between plants and channels, respectively. Each treatment consisted of a 500-L capacity plastic tank to store the nutrient solution, equipped with a float valve that maintained a constant volume (400 L) and a 34-W washing-machine electric drain pump to inject the mixture into the hydroponic channels. An analog timer controlled nutrient solution circulation in the hydroponic channels programmed at alternate intervals of 15 min (turned on for 15 min and off for 15 min), from 6:00 a.m. to 6:00 p.m. From 6:00 p.m. to 6:00 a.m., the nutrient solution was recirculated once every two hours for 15 min.

For Experiment II, an automatic control system earlier reported by Silva et al. (2020b) maintained the treatments with temperature increments of nutrient solutions (+ 2 or + 4°C) using a 2,000-W heating element (D'Volts, Campo Mourão, PR, Brazil). Hence, besides the heater, each plastic tank received a DS18B20 encapsulated digital temperature sensor for continuously monitoring the solution temperature. In tanks of the treatments under ambient RZT, the solution temperatures also were obtained. Each heater was controlled with a single-channel 30V DC – 250V AC/30A relay module at a 5V activation voltage. The DS18B20 temperature sensors and relay modules were connected to the described Arduino Uno board for acquiring air temperature and relative humidity data, with means also recorded every 10 min. For Experiment I, in each plastic tank also was used a temperature sensor. RZTs data are shown in Figures 1A and 1B for Experiments I and II, respectively.



ECw – electrical conductivity of water; ARZT – ambient root-zone temperature; T1 – ECw 0.25 dS m^{-1} (control); T2 – ECw 6.50 dS m^{-1} with NaCl; T3 – ECw 6.50 dS m^{-1} with KCl; T4 – ECw 6.50 dS m^{-1} with $MgCl_2$; T5 – ECw 6.50 dS m^{-1} with $CaCl_2$; T6 – ECw 6.50 dS m^{-1} with NaCl + $CaCl_2$ + $MgCl_2$ in an equivalent 7:2:1 ratio; T7 – ECw 6.50 dS m^{-1} with NaCl + $CaCl_2$ + KCl in an equivalent 7:2:1 ratio. Vertical bars indicate the mean ± standard deviation for a period of 25 days of coriander growth.

Figure 1: Mean hourly temperature of the nutrient solutions during the coriander cultivation in Experiments I (A) and II (B).

Crop and nutrient solution management

Verdão coriander (Feltrin® Sementes, Farroupilha, RS, Brazil) was sown on January 23 and October 8, 2021, respectively for Experiments I and II. Seeds were planted in plastic cups (50 mL capacity with holes at the bottom) filled with a coconut fiber substrate. Three more seeds were added for each desired density when sowing, and thinning was performed later. Irrigations were manually executed with low-salinity water (ECw 0.25 dS m^{-1})

until transplanting (ten days after sowing – DAS).

Densities of 6, 12, 18, 24, or 30 plants were established when transplanting to the hydroponic system after counting the number of plants per cup and distributing 20 bunches of coriander seedlings to each cultivation channel (four for each density). At transplanting, plant height (PH), stem diameter (SD), and shoot fresh matter (SFM) of coriander seedling were determined. Experiment I presented values of 4.97, 5.37, 5.70, 5.47, and 6.27 cm for PH; 0.78, 0.73, 0.79, 0.64, and 0.61 mm for SD; and 0.31, 0.33, 0.34, 0.39, and 0.42 g plant^{-1} for SFM, at densities of 6, 12, 18, 24, and 30 plants bunch^{-1}. Experiment II found values of 5.56, 5.38, 5.20, 5.10, and 6.20 cm for PH; 0.77, 0.76, 0.71, 0.81, and 0.74 mm for SD; and 0.12, 0.15, 0.18, 0.19, and 0.19 g plant^{-1} for SFM.

The water with ECw of 6.50 dS m^{-1} was initially prepared in the treatments under salinity when producing nutrient solutions for the final cultivation system. Experiment I dissolved salts of different cationic natures in low-salinity water (ECw 0.25 dS m^{-1}) in the following quantities: T2 – NaCl (3.63 g L^{-1}), T3 – KCl (4.53 g L^{-1}), T4 – $MgCl_2.2H_2O$ (6.50 g L^{-1}), T5 – $CaCl_2.2H_2O$ (4.55 g L^{-1}), T6 – NaCl + $CaCl_2.2H_2O$ + $MgCl_2.2H_2O$ (in an equivalent 7:2:1 ratio – respectively, 2.54 + 0.90 + 0.65 g L^{-1}), and T7 – NaCl + $CaCl_2.2H_2O$ + KCl (in an equivalent 7:2:1 ratio – respectively, 2.54 + 0.90 + 0.45 g L^{-1}). Experiment II used only NaCl in the same quantity as Experiment I. Subsequently, these waters received fertilizer salts using the standard nutrient solution recommended by Furlani et al. (1999) as a reference for leafy vegetables at 100% concentration.

The following nutrient amounts, in mg L^{-1}, were used: 750 calcium nitrate, 500 potassium nitrate, 150 monoammonium phosphate, and 400 magnesium sulfate. They were obtained separately from the Dripsol® fertilizer (SQM Vitas Brazil, Candeias, BA, Brazil). Micronutrients were provided using 25 mg L^{-1} Micromix® and 16 mg L^{-1} GeoQuel® 13% Fe-EDTA (Rigrantec Tecnologias para Sementes e Plantas Ltda., Porto Alegre, RS, Brazil).

The electrical conductivity of nutrient solutions (ECsol) was measured after fertilizer salt dissolutions (Table 1). During the experiments, the ECsol and pHsol values were measured directly in the plastic tank (three times a week). Overall, the pHsol values oscillated within the recommended range between 5.5 and 6.5 for hydroponic cultivation.

Table 1: Values of electrical conductivity of water (ECw), initial ($ECsol_{initial}$) and final solution ($ECsol_{final}$) of experiments

Treatments^1	--------------Experiment I-----------			------------Experiment II----------------		
	ECw	$ECsol_{initial}$	$ECsol_{final}$	ECw	$ECsol_{initial}^2$	$ECsol_{final}$
			(dS m^{-1})			
T1	0.25	2.04	1.80	0.25	2.15	1.50
T2	6.50	8.00	7.63	6.50	7.92	10.37
T3	6.50	8.00	7.35	0.25	2.15	1.73
T4	6.50	8.00	7.72	6.50	7.92	10.09
T5	6.50	8.00	7.47	0.25	2.15	2.00
T6	6.50	8.00	7.75	6.50	7.92	9.95
T7	6.50	8.00	7.75			

^{1} – details of treatments are presented in Figure 1; ^{2} – values obtained before heating of the nutrient solutions.

Evaluated variables

Both experiments performed two harvests (20 and 25 days after transplanting – DAT). Five plant bunches (one for each density) were collected in each harvest per cultivation channel. Three plants were randomly selected from each bunch to determine the individual measures of plant height (PH, in cm), stem diameter (SD, in mm), shoot fresh matter of the plant (SFM_{plant}, in g $plant^{-1}$), the number of leaves (NL, in leaves $plant^{-1}$), and leaf area (LA, in cm^2 $plant^{-1}$). The data of the three plants provided a mean value. The SD was measured using a digital caliper. LA was measured using a portable leaf area meter model CI202 (CID Bio-Science, Inc., Camas, WA, USA). The SFM of the bunch (SFM_{bunch}, in g $bunch^{-1}$) was obtained by weighing all plants in the cultivation unit.

Statistical analysis

The data were subjected to the normality test (Shapiro-Wilk) and subsequently subjected to analysis of variance by F-test ($p \leq 0.05$). Experiment I separated the means of the main plots using the Scott-Knott test ($p \leq 0.05$). Experiment II compared the means obtained from ECw levels and RTZs with Tukey's test ($p \leq 0.05$). The means from the two ECw levels represented each RZT level. Regression analysis examined the data according to plant density with a significant effect, selecting the first- or second-degree model, and the significance of their parameters was evaluated by Student's t-test.

Results

Visual appearance of the coriander plants

Figures 2 and 3 show the visual aspects of coriander plants under different treatments for Experiments I and II, respectively. Experiment I highlights the bulky aspect and light color of the plant root, regardless of cultivation conditions (Figure 2), indicating that dissolved oxygen (DO) levels in nutrient solutions were adequate for plant growth because they are inversely correlated to the root-zone temperature (RZT). The RZTs in the present study did not exceed 30°C at the hottest time of day (Figure 1A). The roots were less developed and dark in Experiment II (Figures 3E and 3F) due to the higher RZT, especially with ARZT + 4°C (mean of 32.59°C) (Figure 1B).

Regarding the visual aspect of the plant shoot, Experiments I (Figure 2A) and II (Figures 3A, 3C, and 3E) did not register any symptoms of toxicity in coriander leaves cultivated without salt stress (electrical conductivity of water – ECw 0.25 dS m^{-1}). Burning at the edges of older leaves (resulting in necrosis) occurred randomly under salt stress (ECw 6.50 dS m^{-1}) varying with plant density and the cationic nature of salts in Experiment I (Figures 2B-G) or RZTs in Experiment II (Figures 3B, 3D, and 3F). Higher RZTs potentiated the salinity effect in Experiment II, with higher intensity of symptomatic plants under ARZT + 4°C (Figure 3F).

Responses of coriander plants subjected to the isolated and/or combined salt and root-zone temperature stresses

The treatments imposed on the main plots (freshwater and saline water produced with salts of different cationic natures) promoted significant changes ($p \leq 0.01$) in all variables (plant height – PH, stem diameter – SD, number of leaves – NL, leaf area – LA, shoot fresh matter of the plant – SFM_{plant}, and SFM of the bunch of plants – SFM_{bunch}) in both harvests (20 and 25 days after transplanting – DAT) (Table 2). Plant density significantly affected ($p \leq 0.01$) all variables, except PH at 20 DAT. Significant interactions occurred between the treatments and plant densities, except for PH at 20 and 25 DAT, SD at 20 DAT, and the NL and LA at 25 DAT.

Overall, plant growth variables, such as PH (Figure 4A), SD (Figures 4C and 4E), NL (Figures 4F and 4I), and LA (Figures 4K and 4N), showed higher means without salt stress (ECw 0.25 dS m^{-1} – T1) than with salt stress (ECw 6.50 dS m^{-1} produced with salts of different cationic natures: NaCl – T2, KCl – T3, $MgCl_2$ – T4, $CaCl_2$ – T5, NaCl + $CaCl_2$ + $MgCl_2$ in an equivalent 7:2:1 ratio – T6, and NaCl + $CaCl_2$ + KCl in an equivalent 7:2:1 ratio – T7). Coriander PH under the control treatment recorded means of 21.05 and 28.29 cm at 20 and 25 DAT, respectively (Figure 4A). PH was lower under ECw of 6.50 dS m^{-1} for T2 (14.06 cm) and T4 (13.81 cm) at 20 DAT, and at 25 DAT only for T4 (17.50 cm). Regarding the isolated effect of plant density on the harvest at 25 DAT (Figure 4B), PH decreased as the number of plants per cultivation unit increased, varying between 22.35 and 20.22 cm at densities of 6 and 30 plants bunch^{-1}, respectively.

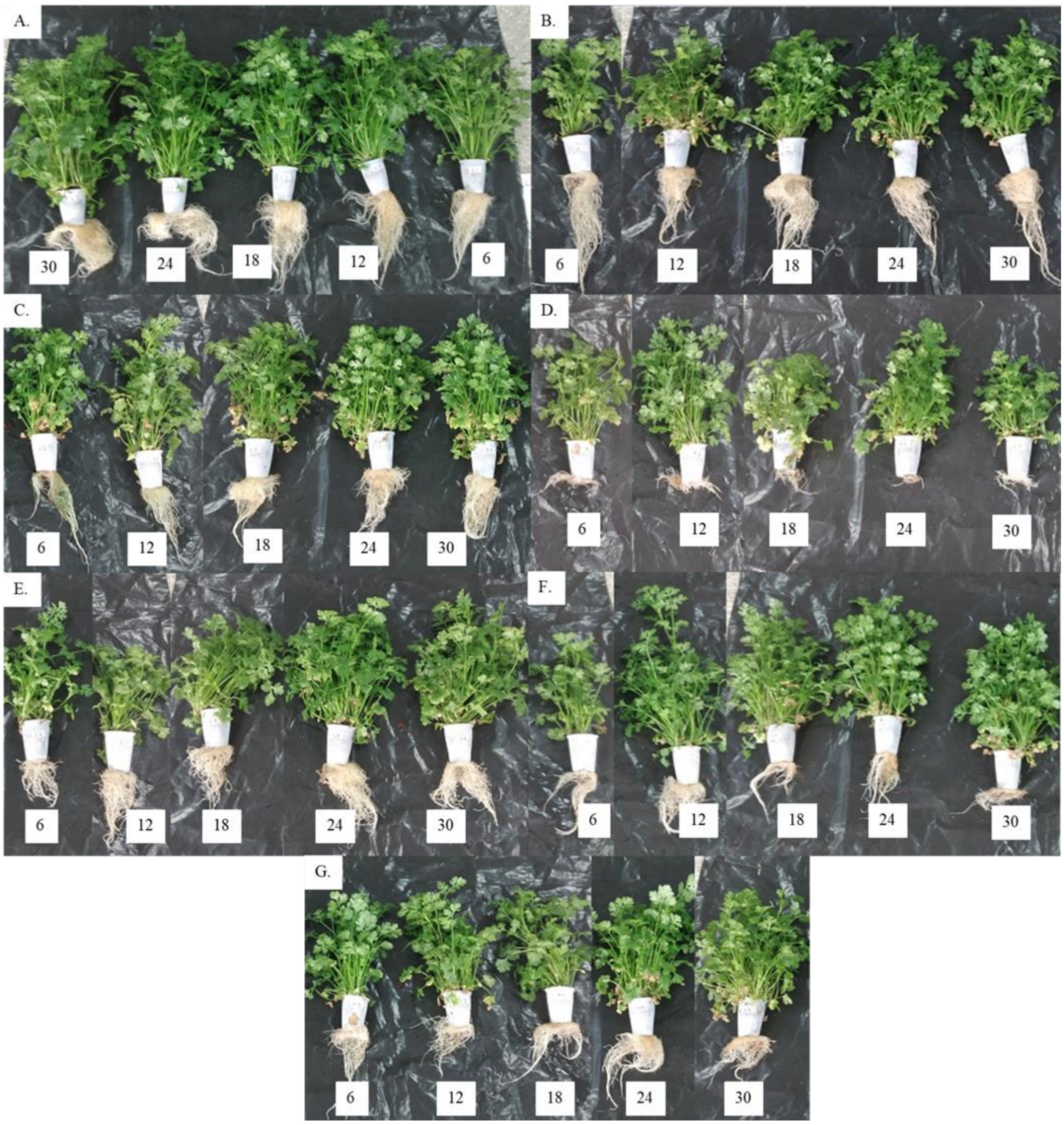


Figure 2: Visual aspect of coriander plants grown at different plant densities and subjected to two levels of electrical conductivity of water (ECw): ECw 0.25 dS m^{-1} (A), ECw 6.50 dS m^{-1} with NaCl (B), ECw 6.50 dS m^{-1} with KCl (C), ECw 6.50 dS m^{-1} with $MgCl_2$ (D), ECw 6.50 dS m^{-1} with $CaCl_2$ (E), ECw 6.50 dS m^{-1} with NaCl + $CaCl_2$ + $MgCl_2$ in an equivalent 7:2:1 ratio (F), and ECw 6.50 dS m^{-1} with NaCl + $CaCl_2$ + KCl in an equivalent 7:2:1 ratio (G) in an NFT hydroponic system, at 25 days after transplanting.

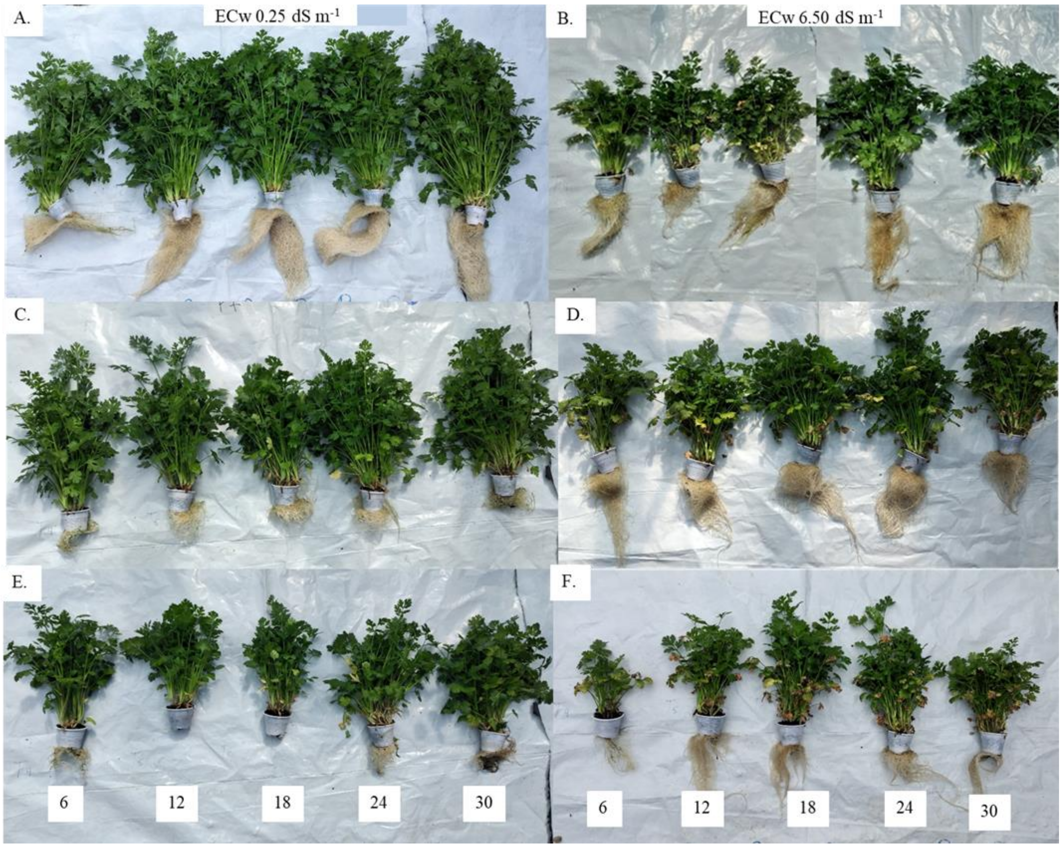
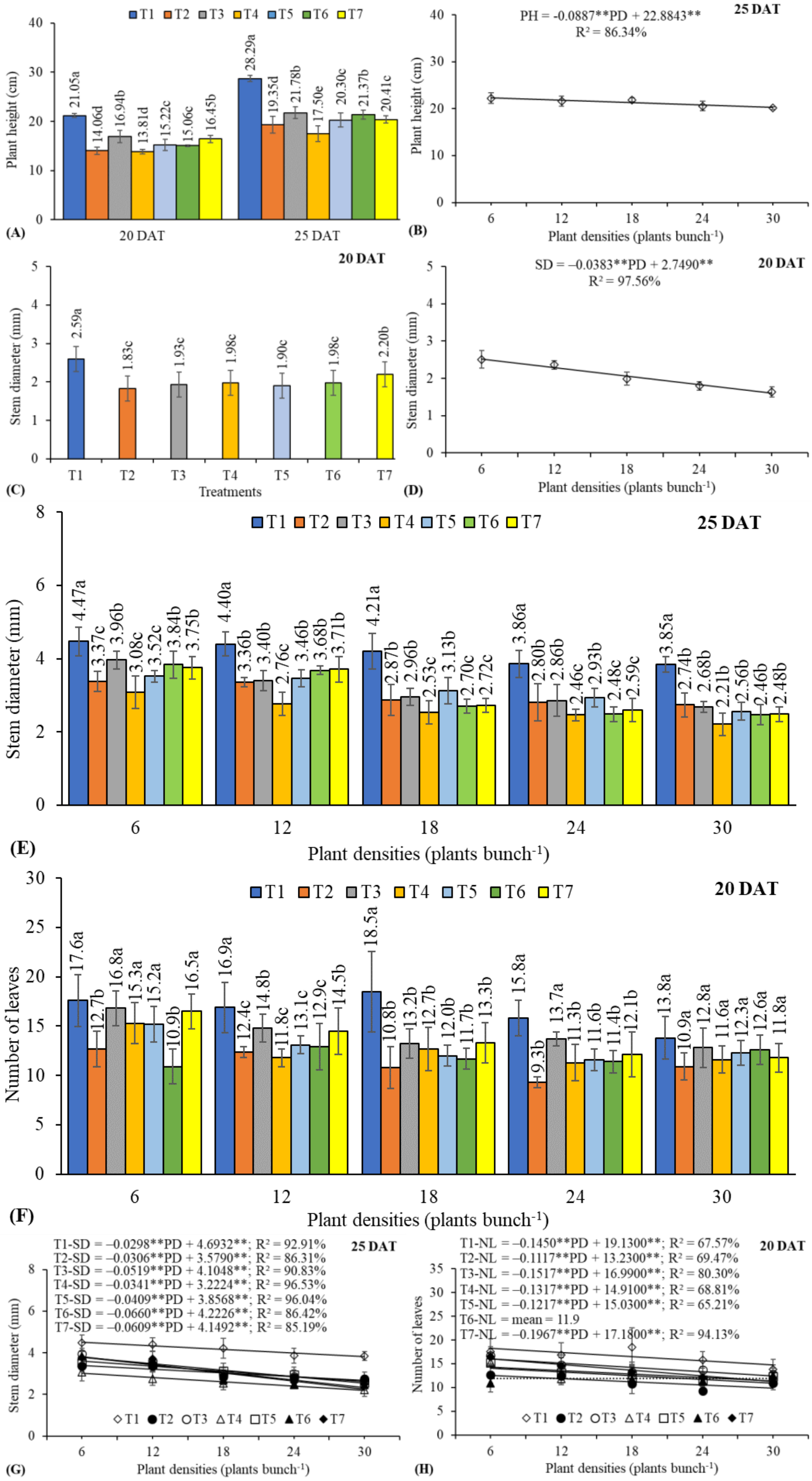


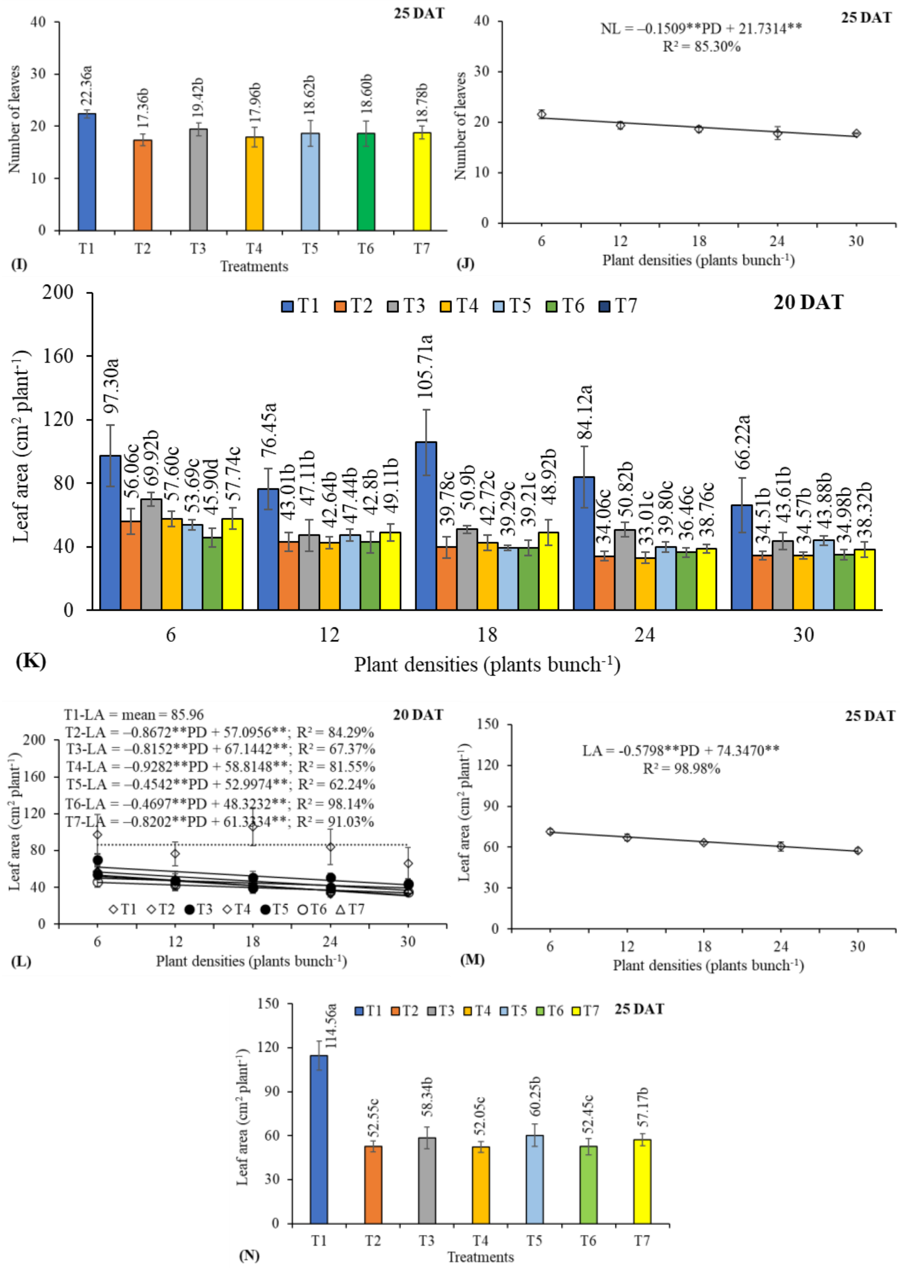
Figure 3: Visual aspect of coriander plants grown at different plant densities and subjected to two levels of electrical conductivity of water (ECw) combined with three root-zone temperatures – RZTs: ambient RZT – ARZT (A and B), ARZT + 2°C (C and D), and ARZT + 4°C (E and F) in an NFT hydroponic system, at 25 days after transplanting.

Table 2: Summary of analysis of variance for plant height (PH), stem diameter (SD), number of leaves (NL), leaf area (LA), shoot fresh matter of the plant (SFM_{plant}), and SFM of the bunch of plants (SFM_{bunch}) of the coriander grown at different plant densities (PD) and subjected to two levels of electrical conductivity of water (freshwater and saline water produced with salts of different cationic natures – Treat) in an NFT hydroponic system, at 20 and 25 days after transplanting (DAT)

SV	PH	SD	NL	LA	SFM_{plant}	SFM_{bunch}
			20 DAT			
Block	*	*	ns	ns	ns	ns
Treat	**	**	**	**	**	**
PD	ns	**	**	**	**	**
Treat × PD	ns	ns	**	**	**	**
CV1 (%)	10.30	16.53	16.98	23.21	23.38	23.86
CV2 (%)	9.60	13.79	12.81	14.95	14.87	15.56
			25 DAT			
Block	ns	ns	ns	ns	ns	ns
Treat	**	**	**	**	**	**
PD	**	**	**	**	**	**
Treat × PD	ns	**	ns	ns	**	**
CV1 (%)	8.37	9.80	11.26	12.20	14.21	20.32
CV2 (%)	9.94	9.53	11.93	10.97	14.69	12.34

SV – source of variation; CV1 and CV2 – coefficients of variation of the errors 1 (main plots) and 2 (subplots), respectively; * and ** – significant at $p \leq 0.05$ and at $p \leq 0.01$, respectively, and ns – not significant by F-test.


(A)
Plant height (cm)
T1 T2 T3 T4 T5 T6 T7
20 DAT: 21.05a 14.06d 16.94b 13.81d 15.22c 15.06c 16.45b
25 DAT: 28.29a 19.35d 21.78b 17.50e 20.30c 21.37b 20.41c
(B)
PH = –0.0887**PD + 22.8843**
R² = 86.34%
25 DAT
Plant height (cm)
Plant densities (plants bunch⁻¹)
6 12 18 24 30
(C)
20 DAT
Stem diameter (mm)
2.59a 1.83c 1.93c 1.98c 1.90c 1.98c 2.20b
T1 T2 T3 T4 T5 T6 T7
Treatments
(D)
SD = –0.0383**PD + 2.7490**
R² = 97.56%
20 DAT
Stem diameter (mm)
Plant densities (plants bunch⁻¹)
(E)
25 DAT
Stem diameter (mm)
6: 4.47a 3.37c 3.96b 3.08c 3.52c 3.84b 3.75b
12: 4.40a 3.36b 3.40b 2.76c 3.46b 3.68b 3.71b
18: 4.21a 2.87b 2.96b 2.53c 3.13b 2.70c 2.72c
24: 3.86a 2.80b 2.86b 2.46c 2.93b 2.48c 2.59c
30: 3.85a 2.74b 2.68b 2.21b 2.56b 2.46b 2.48b
Plant densities (plants bunch⁻¹)
(F)
20 DAT
Number of leaves
6: 17.6a 12.7b 16.8a 15.3a 15.2a 10.9b 16.5a
12: 16.9a 12.4c 14.8b 11.8c 13.1c 12.9c 14.5b
18: 18.5a 10.8b 13.2b 12.7b 12.0b 11.7b 13.3b
24: 15.8a 9.3b 13.7a 11.3b 11.6b 11.4b 12.1b
30: 13.8a 10.9a 12.8a 11.6a 12.3a 12.6a 11.8a
Plant densities (plants bunch⁻¹)
(G)
25 DAT
T1-SD = –0.0298**PD + 4.6932**; R² = 92.91%
T2-SD = –0.0306**PD + 3.5790**; R² = 86.31%
T3-SD = –0.0519**PD + 4.1048**; R² = 90.83%
T4-SD = –0.0341**PD + 3.2224**; R² = 96.53%
T5-SD = –0.0409**PD + 3.8568**; R² = 96.04%
T6-SD = –0.0660**PD + 4.2226**; R² = 86.42%
T7-SD = –0.0609**PD + 4.1492**; R² = 85.19%
Stem diameter (mm)
◇T1 ●T2 ○T3 △T4 □T5 ▲T6 ◆T7
Plant densities (plants bunch⁻¹)
(H)
20 DAT
T1-NL = –0.1450**PD + 19.1300**; R² = 67.57%
T2-NL = –0.1117**PD + 13.2300**; R² = 69.47%
T3-NL = –0.1517**PD + 16.9900**; R² = 80.30%
T4-NL = –0.1317**PD + 14.9100**; R² = 68.81%
T5-NL = –0.1217**PD + 15.0300**; R² = 65.21%
T6-NL = mean = 11.9
T7-NL = –0.1967**PD + 17.1800**; R² = 94.13%
Number of leaves
◇T1 ●T2 ○T3 △T4 □T5 ▲T6 ◆T7
Plant densities (plants bunch⁻¹)



For the isolated effect of the treatments (low-salinity water with ECw of 0.25 dS m^{-1} and saline water with 6.50 dS m^{-1} produced with salts of different cationic natures) (Figures A, C, I, and N) and in the follow-up analysis on the interaction (E, F, and K), means followed by the same letter are not significantly different according to Scott-Knott test ($p \leq 0.05$); ** – significant according to Student's t-test ($p \leq 0.01$); vertical bars indicate the means ± standard deviation.

Figure 4: Plant height – PH (A and B), stem diameter – SD (C, D, E, and G), number of leaves – NL (F, H, I, and J), and leaf area – LA (K, L, M, and N) of coriander plants grown in an NFT hydroponic system.

Plant SD at 20 DAT showed the highest mean of 2.59 mm under the control treatment (ECw 0.25 dS m^{-1}), followed by T7 (2.20 mm) (Figure 4C). The means did not statistically differ in the other treatments (mean of 1.92 mm). As for plant density effects (Figure 4D), SD decreased as the number of plants per bunch increased, with means between 2.52 and 1.60 mm at densities of 6 and 30 plants bunch^{-1}, respectively. The treatment effects in the follow-up analysis at 25 DAT (Figure 4E), except for the density of 30 plants (the means did not statistically differ under ECw

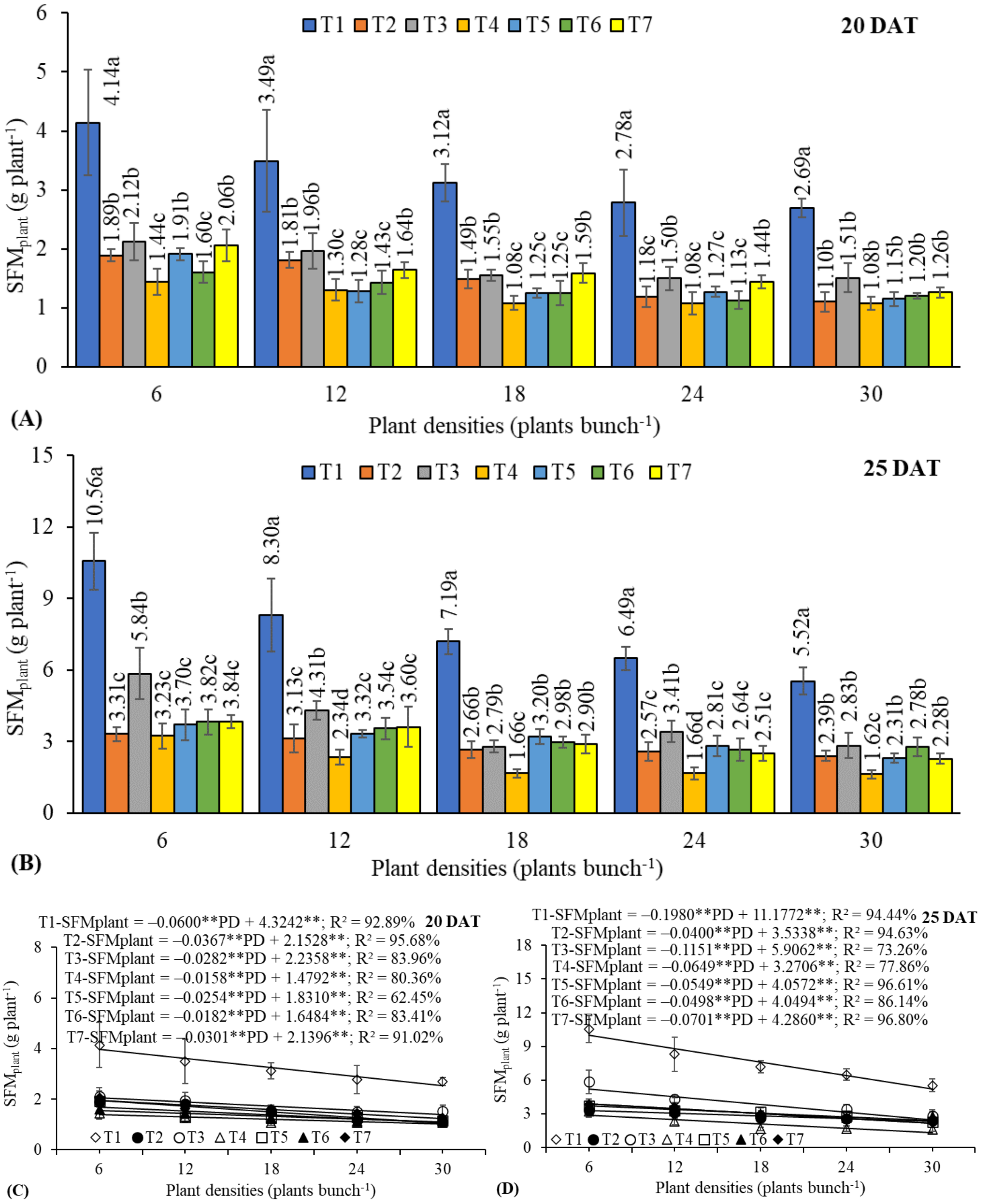
6.50 dS m^{-1} produced with salts of different cationic natures), were divided into three groups, with the highest means occurring for the control – T1 (ECw 0.25 dS m^{-1}), followed by T3, T6, and T7 at the density of 6 plants; T2, T3, T5, T6, and T7 at the density of 12 plants; and T2, T3, and T5 at densities of 18 and 24 plants. SD decreased as the number of plants per bunch increased, regardless of the treatment (Figure 4G). The variations at densities of 6 and 30 plants $bunch^{-1}$ were 4.51 and 3.80 mm for T1, 3.39 and 2.66 mm for T2, 3.79 and 2.55 mm for T3, 3.02 and 2.20 mm for T4, 3.61 and 2.63 mm for T5, 3.83 and 2.24 mm for T6, and 3.78 and 2.32 mm for T7.

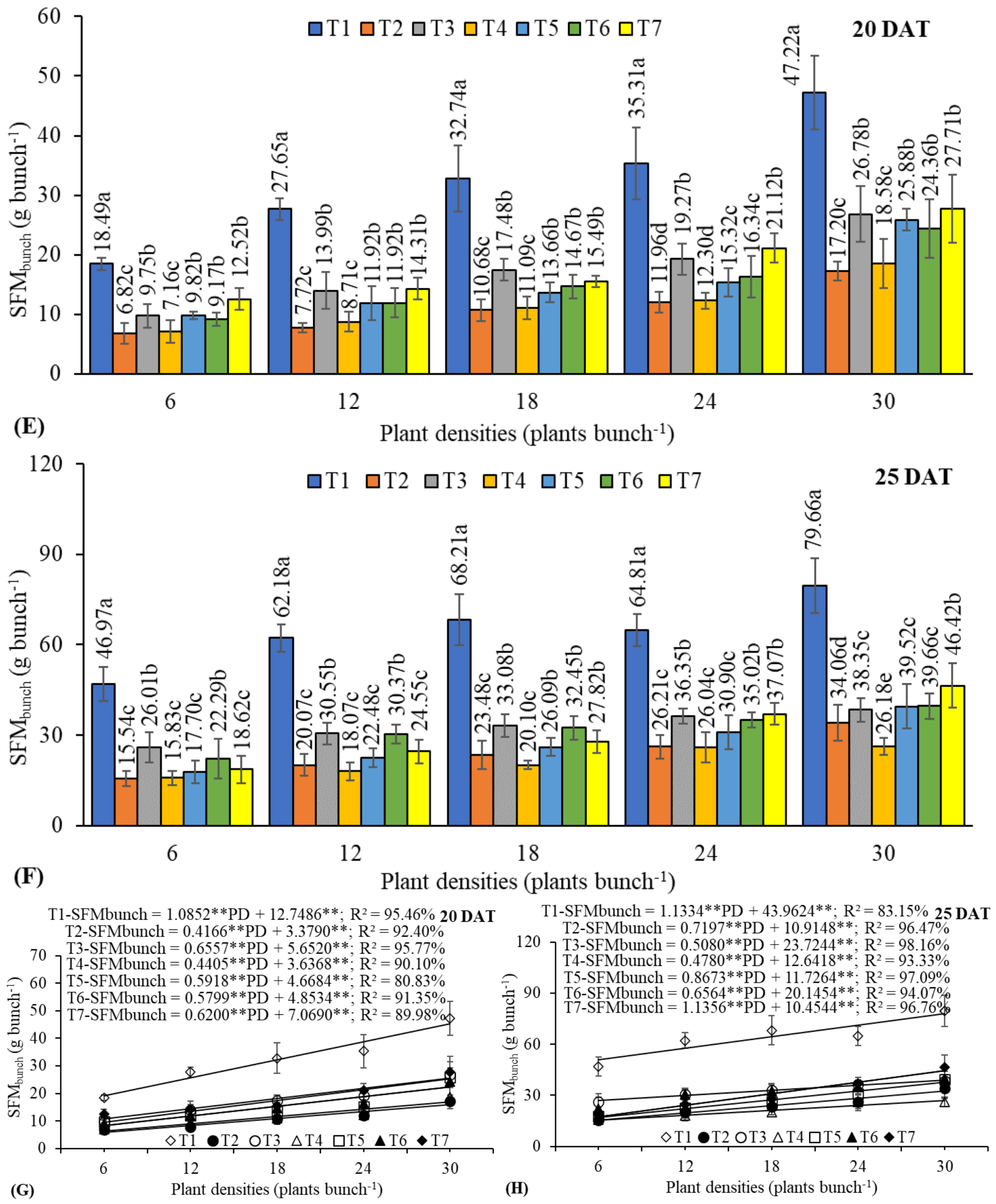
The follow-up analysis of NL at 20 DAT (Figure 4F), did not show statistically different means in the seven treatments cultivated at the density of 30 plants. The treatment effects at densities of 6, 18, and 24 plants were divided into two groups, with the highest mean for T1 alone (density of 18 plants) or combined with T3, T4, T5, and T7 (density of 6 plants), or T3 (density of 24 plants). The means at the density of 12 plants were divided into three groups: T1; T3 and T7; and T2, T4, T5, and T6. Similar to the previous variables, NL decreased as the number of plants per bunch increased when evaluating plant densities in each treatment, except for T6 (mean of 11.9 leaves $plant^{-1}$) (Figure 4H). The variations at densities of 6 and 30 plants $bunch^{-1}$ were 18.26 and 14.78 leaves $plant^{-1}$ for T1, 12.56 and 9.88 leaves $plant^{-1}$ for T2, 16.08 and 12.44 leaves $plant^{-1}$ for T3, 14.12 and 10.96 leaves $plant^{-1}$ for T4, 14.30 and 11.38 leaves $plant^{-1}$ for T5, and 16.00 and 11.28 leaves $plant^{-1}$ for T7. The isolated effect of plant density at 25 DAT yielded 20.83 and 17.20 leaves $plant^{-1}$ at densities of 6 and 30 plants $bunch^{-1}$, respectively (Figure 4J). The isolated treatment effects showed 22.36 leaves $plant^{-1}$ without salt stress and a mean of 18.46 leaves $plant^{-1}$ with ECw of 6.50 dS m^{-1}, regardless of the cationic nature of the salts (Figure 4I).

Similar to NL, the treatments responded differently to plant density in the follow-up analysis of LA at 20 DAT (Figure 4K). For instance, the means did not statistically differ under cultivation with salt stress at densities of 12 and 30 plants $bunch^{-1}$, regardless of the cationic nature of salts. LA decreased as the number of plants per bunch increased, except for T1 (mean of 85.96 cm^2 $plant^{-1}$) (Figure 4L). The variations at densities of 6 and 30 plants $bunch^{-1}$ were 51.89 and 31.08 cm^2 $plant^{-1}$ for T2, 62.25 and 42.69 cm^2 $plant^{-1}$ for T3, 53.24 and 30.97 cm^2 $plant^{-1}$ for T4, 50.27 and 39.37 cm^2 $plant^{-1}$ for T5, 45.51 and 34.23 cm^2 $plant^{-1}$ for T6, and 56.41 and 36.73 cm^2 $plant^{-1}$ for T7. At 25 DAT, the variations at densities of 6 and 30 plants $bunch^{-1}$ were 70.87 and 56.95 cm^2 $plant^{-1}$, respectively (Figure 4M). As for treatment effects, the highest mean occurred in the control (114.56 cm^2 $plant^{-1}$), followed by T3, T5, and T7 (58.59 cm^2 $plant^{-1}$) (Figure 4N).

Plant biomass production had similar responses when treatment effects varied according to plant density (Figures 5A and 5B), as in the plant growth variables (SD, NL, and LA). Therefore, the highest means occurred under ECw of 0.25 dS m^{-1}, namely 4.14, 3.49, 3.12, 2.78, and 2.69 g $plant^{-1}$ at 20 DAT (Figure 5A) and 10.56, 8.30, 7.19, 6.49, and 5.52 g $plant^{-1}$ at 25 DAT (Figure 5B) at densities of 6, 12, 18, 24, and 30 plants $bunch^{-1}$, respectively. The follow-up analysis of plant densities in each treatment resulted in 3.96 and 9.99 g $plant^{-1}$ at 20 DAT (Figure 5C) and 25 DAT (Figure 5D) at the density of 6 plants $bunch^{-1}$ and 2.52 and 5.24 g $plant^{-1}$ at the density of 30 plants $bunch^{-1}$, respectively, for T1; 1.93 and 3.29 g $plant^{-1}$ and 1.05 and 2.33 g $plant^{-1}$ for T2; 2.07 and 5.21 g $plant^{-1}$ and 1.39 and 2.45 g $plant^{-1}$ for T3; 1.38 and 2.88 g $plant^{-1}$ and 1.00 and 1.32 g $plant^{-1}$ for T4; 1.68 and 3.73 g $plant^{-1}$ and 1.07 and 2.41 g $plant^{-1}$ for T5; 1.54 and 3.75 g $plant^{-1}$ and 1.10 and 2.55 g $plant^{-1}$ for T6; 2.08 and 3.86 g $plant^{-1}$ and 1.83 and 2.18 g $plant^{-1}$ for T7.

Treatment effects varied according to plant density on SFM_{bunch} (Figures 5E and 5F), as observed for SFM_{plant}. The control treatment (ECw 0.25 dS m^{-1}) showed means of 18.49, 27.65, 32.74, 35.31, and 47.22 g bunch^{-1} at 20 DAT (Figure 5E) and 46.97, 62.18, 68.21, 64.81, and 79.66 g bunch^{-1} at 25 DAT (Figure 5F) at densities of 6, 12, 18, 24, and 30 plants bunch^{-1}, respectively. Unlike the evaluated variables per plant, biomass accumulation increased as the number of plants per bunch increased. The follow-up analysis of plant densities in each treatment resulted in 19.26 and 50.76 g bunch^{-1} at 20 DAT (Figure 5G) and 25 DAT (Figure 5H) at the density of 6 plants and 45.30 and 77.96 g bunch^{-1} at the density of 30 plants bunch^{-1}, respectively, for T1; 5.88 and 15.23 g bunch^{-1} and 15.88 and 32.50 g bunch^{-1} for T2; 9.59 and 26.77 g bunch^{-1} and 25.32 and 38.96 g bunch^{-1} for T3; 6.28 and 15.51 g bunch^{-1} and 16.85 and 26.98 g bunch^{-1} for T4; 8.22 and 16.93 g bunch^{-1} and 22.42 and 37.74 g bunch^{-1} for T5; 8.33 and 24.08 g bunch^{-1} and 22.25 and 39.84 g bunch^{-1} for T6; 10.79 and 17.27 g bunch^{-1} and 25.67 and 44.52 g bunch^{-1} for T7.





In Figures A, B, E, and F – means of the treatments (low-salinity water with ECw of 0.25 dS m^{-1} and saline water with 6.50 dS m^{-1} produced with salts of different cationic natures) followed by the same letter are not significantly different according to Scott-Knott test ($p \leq 0.05$) within each plant density; ** – significant according to Student's t-test ($p \leq 0.01$); vertical bars indicate the means ± standard deviation.

Figure 5: Shoot fresh matter of the plant – SFM_{plant} (A-D) and SFM of the bunch of plants – SFM_{bunch} (E-H) of the coriander grown in an NFT hydroponic system.

The isolated impact of factors (RZTs, ECw, or plant density) in both harvests (20 and 25 DAT) significantly influenced ($p \leq 0.01$) all variables (PH, SD, NL, LA, SFM_{plant}, and SFM_{bunch}) in Experiment II (Table 3). All variables evaluated at 20 and 25 DAT demonstrated a significant interaction ($p \leq 0.01$) between RZT and ECw. The interaction between ECw and plant density did not affect ($p > 0.05$) the PH and SD at 20 and 25 DAT and NL and LA at 20 DAT. The interaction between RZT and plant density was not significant ($p > 0.05$) only for PH and SD at 20 and 25 DAT. The three factors showed a significant interaction, except for PH and SD at 20 and 25 DAT.

Table 3: Summary of analysis of variance for plant height (PH), stem diameter (SD), number of leaves (NL), leaf area (LA), shoot fresh matter of the plant (SFM_{plant}), and SFM of the bunch of plants (SFM_{bunch}) of the coriander grown at different plant densities (PD) and subjected to two levels of electrical conductivity of water (ECw) and different root-zone temperatures (RZTs) in an NFT hydroponic system, at 20 and 25 days after transplanting (DAT)

SV	PH	SD	NL	LA	SFM_{plant}	SFM_{bunch}
			20 DAT			
Block	ns	ns	ns	ns	ns	ns
ECw	**	**	**	**	**	**
RZT	**	**	**	**	**	**
ECw × RZT	**	**	**	**	**	**
PD	**	**	**	**	**	**
ECw × PD	ns	ns	ns	ns	**	**
RZT × PD	ns	ns	**	**	**	**
ECw × RZT × PD	ns	ns	*	*	**	**
CV1 (%)	10.93	19.46	16.72	24.88	11.82	9.95
CV2 (%)	8.50	14.01	11.89	17.21	19.77	11.52
			25 DAT			
Block	ns	ns	ns	ns	ns	ns
ECw	**	**	**	**	**	**
RZT	**	**	**	**	**	**
ECw × RZT	**	**	**	**	**	**
PD	**	**	**	**	**	**
ECw × PD	ns	ns	**	**	**	**
RZT × PD	ns	ns	**	**	**	**
ECw × RZT × PD	ns	ns	**	**	*	**
CV1 (%)	12.32	15.88	14.75	15.25	17.03	12.72
CV2 (%)	8.19	9.22	10.84	13.59	17.95	16.51

SV – source of variation; CV1 and CV2 – coefficients of variation of the errors 1 (main plots) and 2 (subplots), respectively; * and ** – significant at $p \leq 0.05$ and at $p \leq 0.01$, respectively, and ns – not significant by F-test.

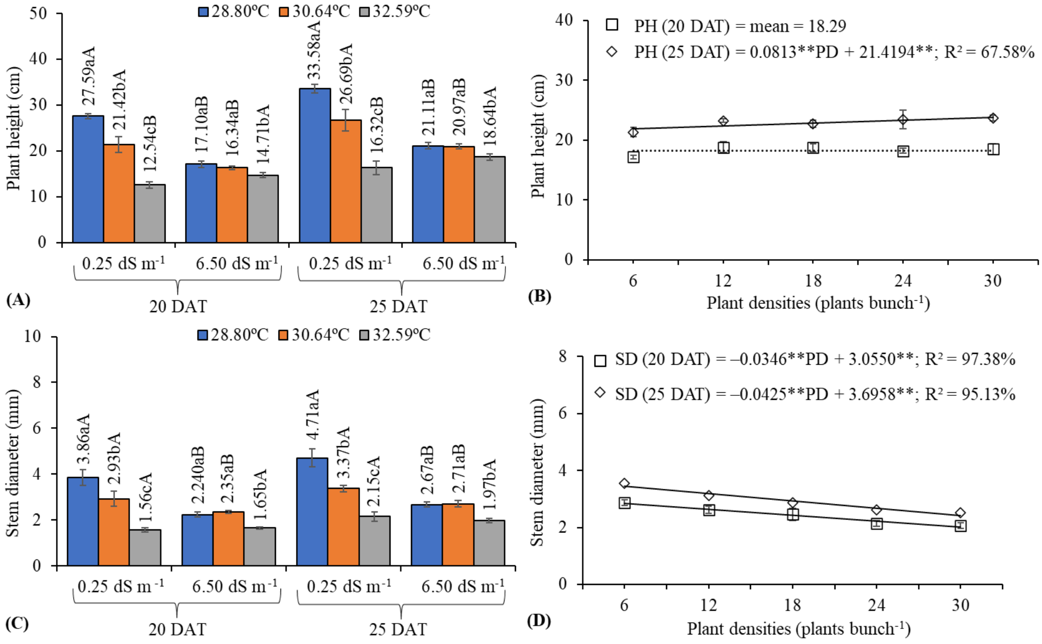
The follow-up analysis of coriander PH for ECw levels in each RZT resulted in 27.59 and 21.42 cm at 20 DAT and 33.58 and 26.69 cm at 25 DAT with ARZT (mean of 28.80°C) and ARZT + 2°C (mean of 30.64°C), respectively, for the control treatment without salt stress; 17.10 and 16.34 cm and 21.11 and 20.97 cm under salt stress (Figure 6A). With higher temperature (ARZT + 4°C, mean of 32.59°C), showed higher means under salt stress than without salt stress. Similar to PH, the higher means of SD were recorded without salt stress within ARZT and ARZT + 2°C. At ARZT + 4°C, the means did not statistically differ as a function of the ECw levels (Figure 6C). As for plant density effects, PH mean of 18.29 cm at 20 DAT was obtained, regardless of the number of plants per bunch. At 25 DAT, PH increased as the number of plants per bunch, with means between 21.91 and 23.86 cm at densities of 6 and 30 plants $bunch^{-1}$, respectively (Figure 6B). SD decreased as the number of plants per bunch increased, with means between 2.85 and 2.02 mm at 20 DAT and 3.44 and 2.42 mm at 25 DAT at densities of 6 and 30 plants $bunch^{-1}$, respectively (Figure 6D).

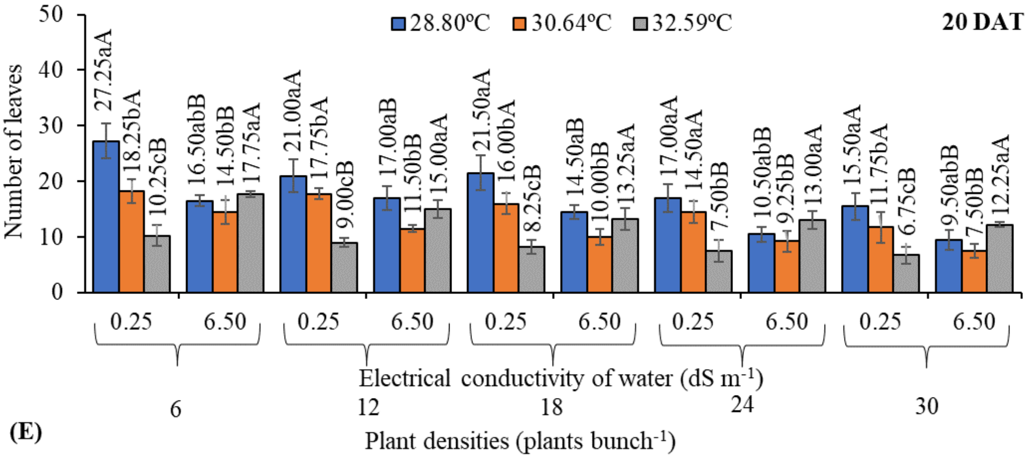
Behavior similar to PH was observed in the follow-up analysis of NL at 20 DAT for ECw and RZT levels in all plant densities (Figure 6E). At 25 DAT (Figure 6F), the behavior was maintained for all plant densities, except with higher ARZT + 4°C. In this case, the means did not statistically differ as a function of the ECw levels at densities of 6, 12, and 18 plants $bunch^{-1}$;

while the means at the densities of 24 and 30 plants bunch^{-1} were lower under salt stress (ECw 6.50 dS m^{-1}). NL decreased as the number of plants per bunch increased, with variations at densities of 6 and 30 plants bunch^{-1} between 25.95 and 14.95 leaves plant^{-1} at 20 DAT (Figure 6G) and 44.25 and 25.95 leaves plant^{-1} at 25 DAT (Figure 6H), respectively, under ECw of 0.25 dS m^{-1} and ARZT; 17.70 and 9.50 leaves plant^{-1} and 22.40 and 15.10 leaves plant^{-1} under ECw of 6.50 dS m^{-1} and ARZT; 18.90 and 12.40 leaves plant^{-1} and 34.15 and 19.05 leaves plant^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 2ºC; 13.80 and 7.30 leaves plant^{-1} and 15.55 and 11.15 leaves plant^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 2ºC; 10.05 and 6.65 leaves plant^{-1} and 22.20 and 18.20 leaves plant^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 4ºC; 16.85 and 11.65 leaves plant^{-1} and 21.65 and 13.45 leaves plant^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 4ºC.

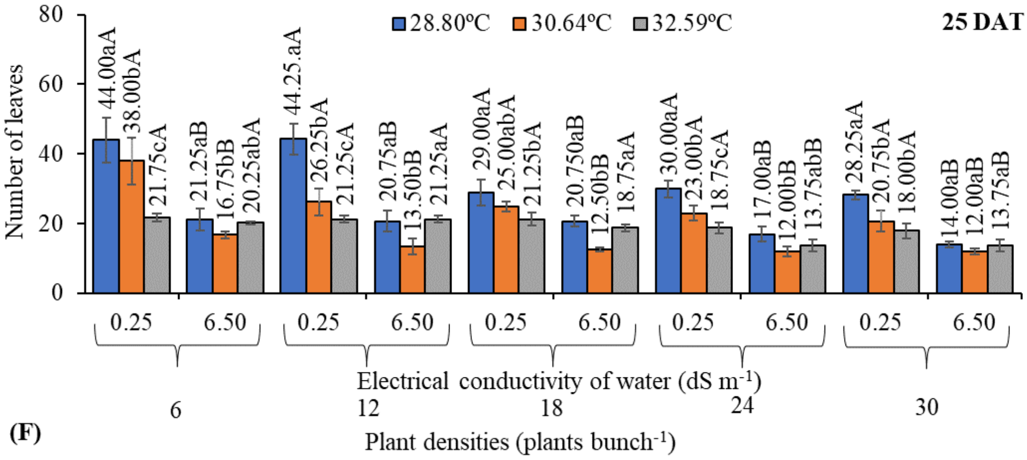
For LA at 20 DAT (Figure 6I), showed higher means without salt stress than with salt stress with ARZT and ARZT + 2°C in all plant densities; while with ARZT + 4°C, higher means were obtained under salt stress. At 25 DAT (Figure 6J), higher means were obtained without salt stress in all RZTs (ARZT, ARZT + 2°C, and ARZT + 4°C).

The variations at densities of 6 and 30 plants bunch^{-1} were 138.44 and 90.20 cm^2 plant^{-1} at 20 DAT (Figure 6K) and 288.95 and 134.66 cm^2 plant^{-1} at 25 DAT (Figure 6L), respectively, under ECw of 0.25 dS m^{-1} and ARZT; 76.05 and 30.49 cm^2 plant^{-1} and 108.43 and 24.82 cm^2 plant^{-1} under ECw of 6.50 dS m^{-1} and ARZT; 98.68 and 52.06 cm^2 plant^{-1} and 150.90 and 72.18 cm^2 plant^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 2ºC; 47.46 and 32.81 cm^2 plant^{-1} and 36.35 and 16.94 cm^2 plant^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 2ºC; 26.28 and 16.85 cm^2 plant^{-1} and 77.87 and 51.00 cm^2 plant^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 4ºC; 51.08 and 30.56 cm^2 plant^{-1} and 43.92 and 32.87 cm^2 plant^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 4ºC.

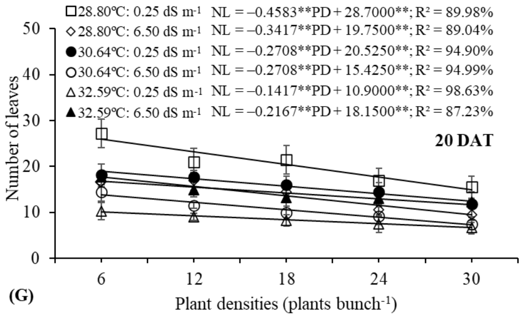



Number of leaves
50
40
30
20
10
0
■28.80ºC ■30.64ºC ■32.59ºC
20 DAT
27.25aA
18.25bA
10.25cB
16.50abB
14.50bB
17.75aA
21.00aA
17.75bA
9.00cB
17.00aB
11.50bB
15.00aA
21.50aA
16.00bA
8.25cB
14.50aB
10.00bB
13.25aA
17.00aA
14.50aA
7.50bB
10.50abB
9.25bB
13.00aA
15.50aA
11.75bA
6.75cB
9.50abB
7.50bB
12.25aA
0.25
6.50
Electrical conductivity of water (dS m-1)
6
12
18
24
30
Plant densities (plants bunch-1)

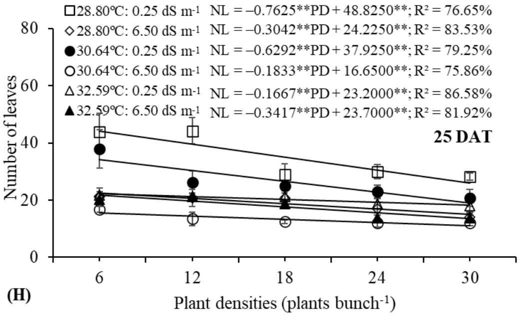
(E)


Number of leaves
80
60
40
20
0
■28.80ºC ■30.64ºC ■32.59ºC
25 DAT
44.00aA
38.00bA
21.75cA
21.25aB
16.75bB
20.25abA
44.25aA
26.25bA
21.25cA
20.75aB
13.50bB
21.25aA
29.00aA
25.00abA
21.25bA
20.750aB
12.50bB
18.75aA
30.00aA
23.00bA
18.75cA
17.00aB
12.00bB
13.75abB
28.25aA
20.75bA
18.00bA
14.00aB
12.00aB
13.75aB
0.25
6.50
Electrical conductivity of water (dS m-1)
6
12
18
24
30
Plant densities (plants bunch-1)

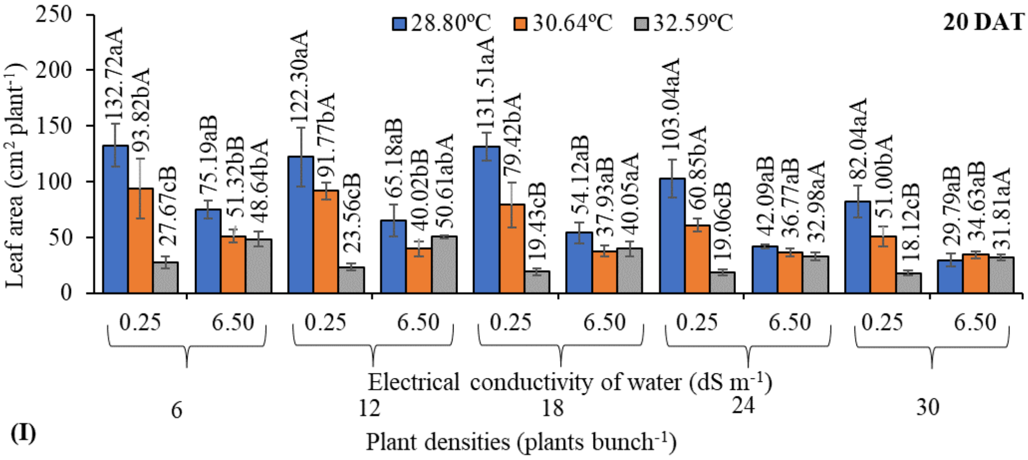
(F)


□28.80ºC: 0.25 dS m-1 NL = –0.4583**PD + 28.7000**; R² = 89.98%
◇28.80ºC: 6.50 dS m-1 NL = –0.3417**PD + 19.7500**; R² = 89.04%
●30.64ºC: 0.25 dS m-1 NL = –0.2708**PD + 20.5250**; R² = 94.90%
○30.64ºC: 6.50 dS m-1 NL = –0.2708**PD + 15.4250**; R² = 94.99%
△32.59ºC: 0.25 dS m-1 NL = –0.1417**PD + 10.9000**; R² = 98.63%
▲32.59ºC: 6.50 dS m-1 NL = –0.2167**PD + 18.1500**; R² = 87.23%
20 DAT
Number of leaves
50
40
30
20
10
0
6
12
18
24
30
Plant densities (plants bunch-1)

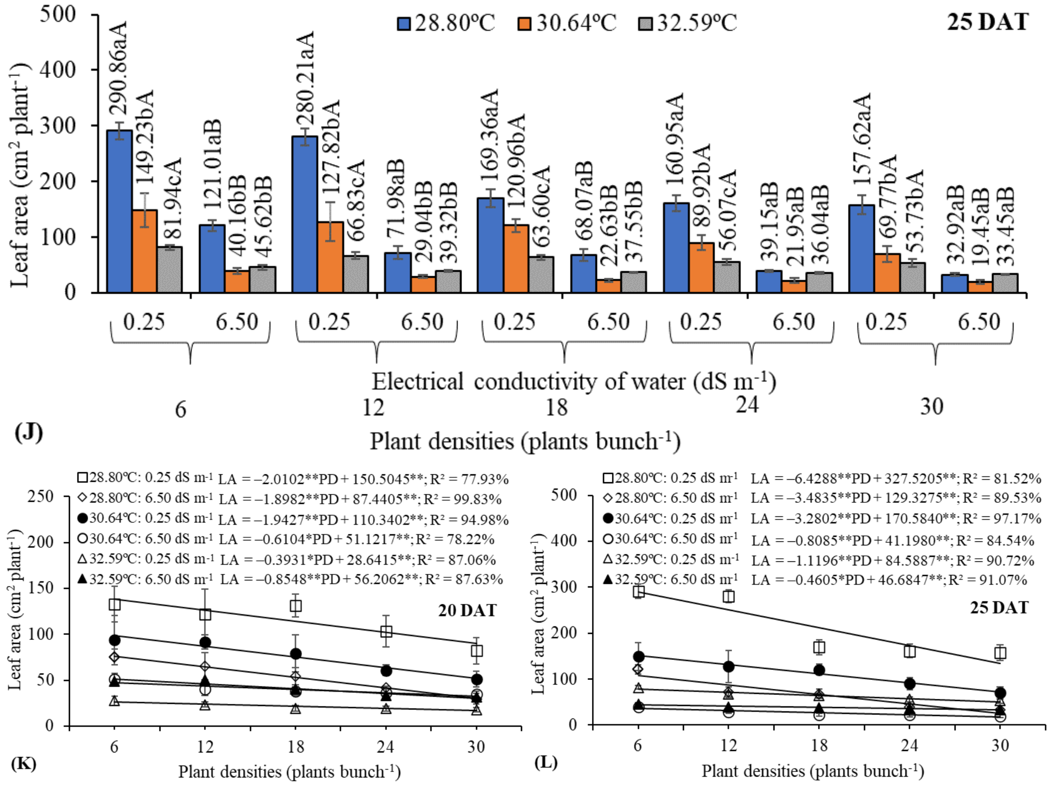
(G)


□28.80ºC: 0.25 dS m-1 NL = –0.7625**PD + 48.8250**; R² = 76.65%
◇28.80ºC: 6.50 dS m-1 NL = –0.3042**PD + 24.2250**; R² = 83.53%
●30.64ºC: 0.25 dS m-1 NL = –0.6292**PD + 37.9250**; R² = 79.25%
○30.64ºC: 6.50 dS m-1 NL = –0.1833**PD + 16.6500**; R² = 75.86%
△32.59ºC: 0.25 dS m-1 NL = –0.1667**PD + 23.2000**; R² = 86.58%
▲32.59ºC: 6.50 dS m-1 NL = –0.3417**PD + 23.7000**; R² = 81.92%
25 DAT
Number of leaves
80
60
40
20
0
6
12
18
24
30
Plant densities (plants bunch-1)

(H)


Leaf area (cm² plant-1)
250
200
150
100
50
0
■28.80ºC ■30.64ºC ■32.59ºC
20 DAT
132.72aA
93.82bA
27.67cB
75.19aB
51.32bB
48.64bA
122.30aA
91.77bA
23.56cB
65.18aB
40.02bB
50.61abA
131.51aA
79.42bA
19.43cB
54.12aB
37.93aB
40.05aA
103.04aA
60.85bA
19.06cB
42.09aB
36.77aB
32.98aA
82.04aA
51.00bA
18.12cB
29.79aB
34.63aB
31.81aA
0.25
6.50
Electrical conductivity of water (dS m-1)
6
12
18
24
30
Plant densities (plants bunch-1)

(I)

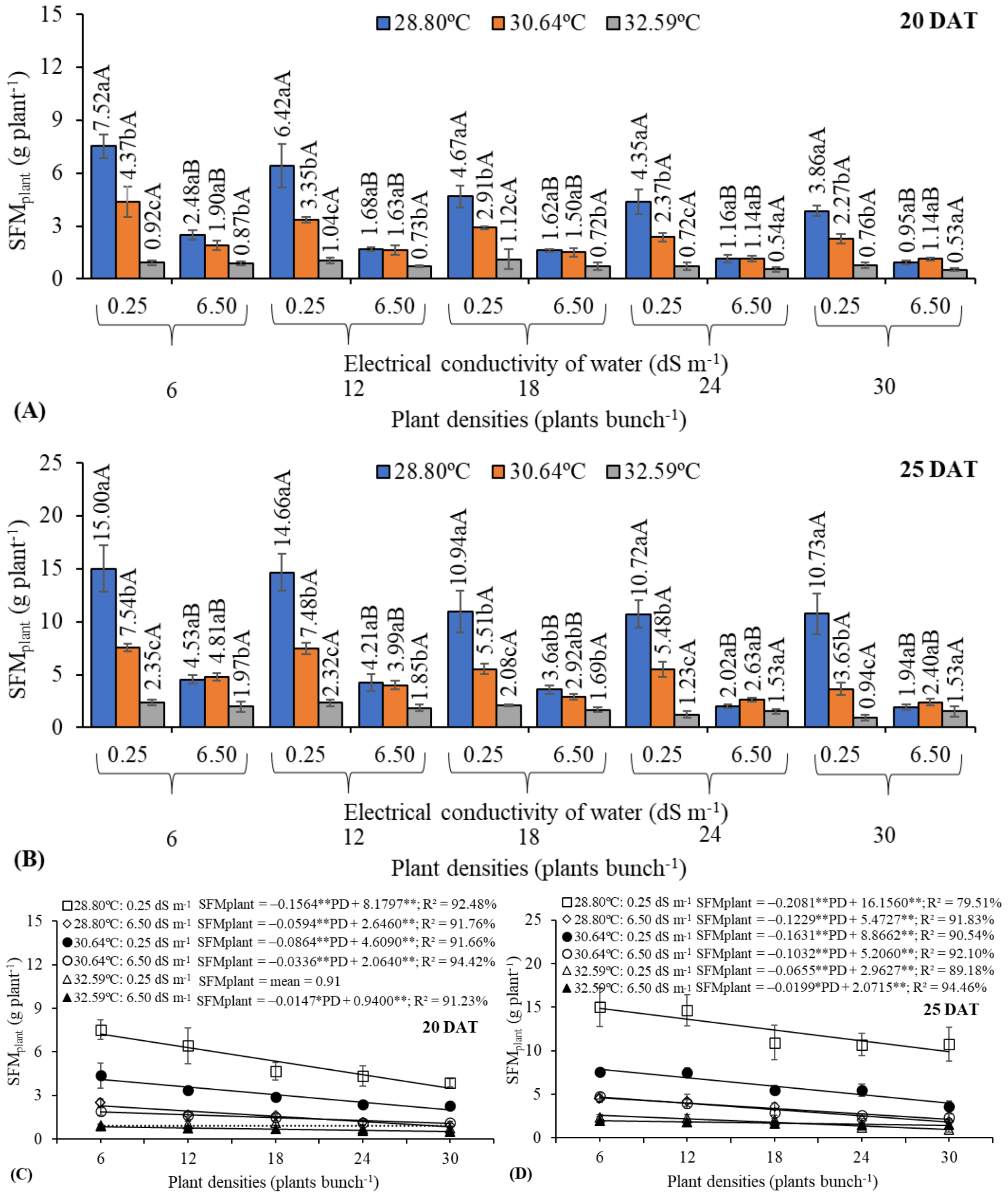


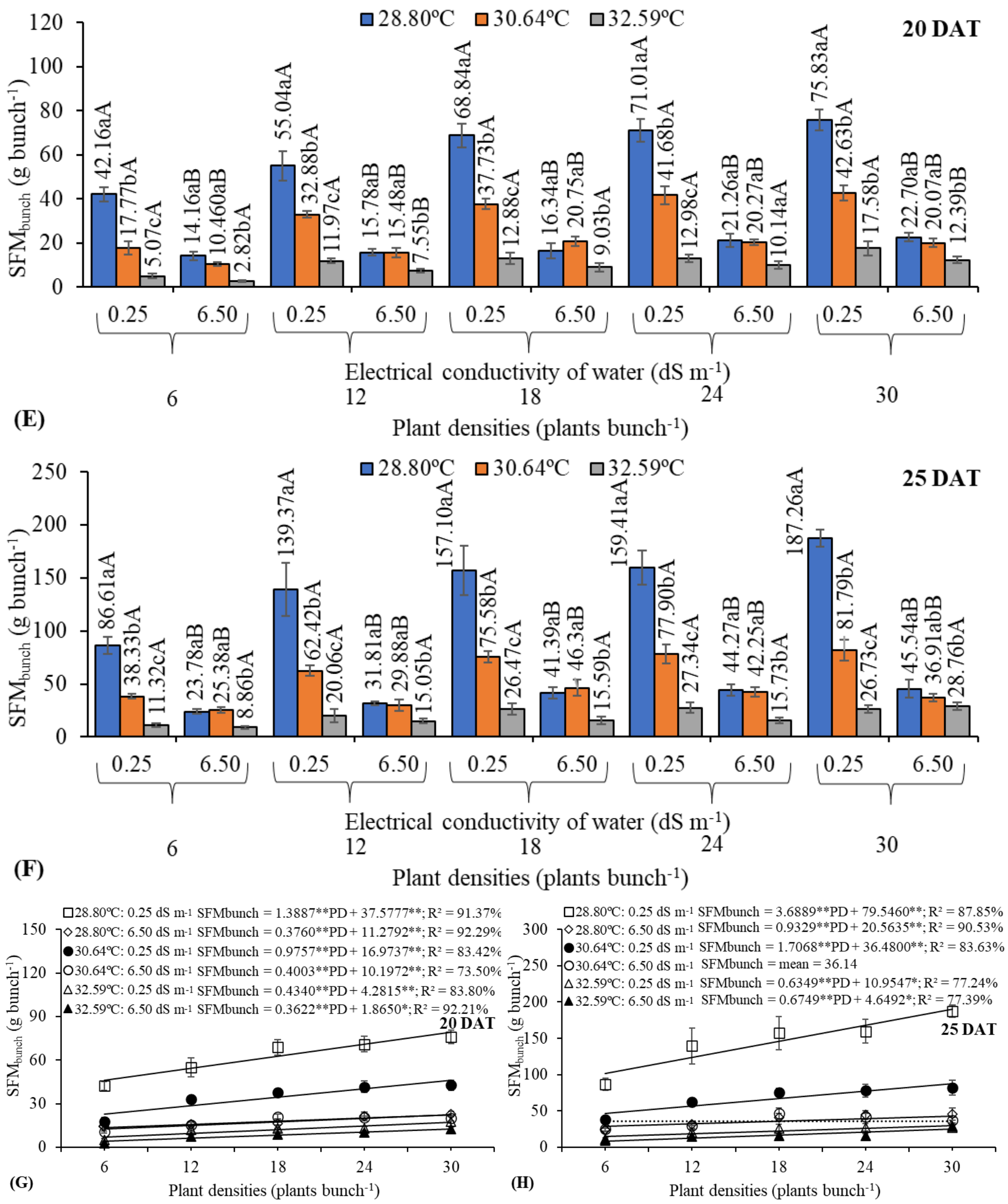
In Figures A, C, E, F, I and J, the lowercase letters compare the means of RZT levels within each ECw level and uppercase letters compare the means of ECw levels within each RZT level, according to Tukey's test ($p \leq 0.05$); **, * – significant at $p \leq 0.01$ and $p \leq 0.05$, respectively, according to Student's t-test; vertical bars indicate the means ± standard deviation.

Figure 6: Plant height – PH (A and B), stem diameter – SD (C and D), number of leaves – NL (E-H), and leaf area – LA (I-L) of the coriander plants grown in an NFT hydroponic system.

Similar to the previous variables, in the follow-up analysis of SFM_{plant} at 20 DAT (Figure 7A) and 25 DAT (Figure 7B), the behavior of the ECw levels with ARZT and ARZT + 2ºC was maintained for all plant densities. At higher ARZT + 4°C, the means did not statistically differ as a function of the ECw levels, regardless of plant densities. SFM_{plant} decreased as the number of plants per bunch increased, except at 20 DAT under ECw of 0.25 dS m^{-1} and ARZT + 4ºC (mean of 0.91 g $plant^{-1}$) (Figure 7C). The variations at densities of 6 and 30 plants $bunch^{-1}$ were 7.24 and 3.49 g $plant^{-1}$ under ECw of 0.25 dS m^{-1} and ARZT; 2.29 and 0.86 g $plant^{-1}$ under ECw of 6.50 dS m^{-1} and ARZT; 4.09 and 2.02 g $plant^{-1}$ under ECw of 0.25 dS m^{-1} and ARZT + 2ºC; 1.86 and 1.06 g $plant^{-1}$ under ECw of 6.50 dS m^{-1} and ARZT + 2ºC; 0.85 and 0.50 g $plant^{-1}$ under ECw of 6.50 dS m^{-1} and ARZT + 4ºC. At 25 DAT (Figure 7D), the variations were 14.91 and 9.91 g $plant^{-1}$ under ECw of 0.25 dS m^{-1} and ARZT; 4.73 and 1.78 g $plant^{-1}$ under ECw of 6.50 dS m^{-1} and ARZT; 7.89 and 3.97 g $plant^{-1}$ under ECw of 0.25 dS m^{-1} and ARZT + 2ºC; 4.59 and 2.11 g $plant^{-1}$ under ECw of 6.50 dS m^{-1} and ARZT + 2ºC; 2.57 and 1.00 g $plant^{-1}$ under ECw of 0.25 dS m^{-1} and ARZT + 4ºC; 1.95 and 1.47 g $plant^{-1}$ under ECw of 6.50 dS m^{-1} and ARZT + 4ºC.

For SFM_{bunch}, the behavior of the ECw levels with ARZT and ARZT + 2ºC was maintained for all plant densities at 20 DAT (Figure 7E) and 25 DAT (Figure 7F). At higher ARZT + 4°C, means at the densities of 12 and 30 plants $bunch^{-1}$ were lower under salt stress and in other densities did not statistically differ (behavior similar to 25 DAT, regardless of plant densities). Unlike the evaluated variables per plant, SFM_{bunch} increased as the number of plants per bunch increased, except at 25 DAT under ECw of 6.50 dS m^{-1} and ARZT + 2ºC (mean of 36.14 g bunch^{-1}) (Figure 7H). At 20 DAT (Figure 7G), the variations at densities of 6 and 30 plants bunch^{-1} were 45.91 and 79.24 g bunch^{-1} under ECw of 0.25 dS m^{-1} and ARZT; 13.53 and 22.56 g bunch^{-1} under ECw of 6.50 dS m^{-1} and ARZT; 22.83 and 46.24 g bunch^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 2ºC; 12.60 and 22.21 g bunch^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 2ºC; 6.88 and 17.30 g bunch^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 4ºC; 4.04 and 12.73 g bunch^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 4ºC. At 25 DAT, the variations were 101.68 and 190.21 g bunch^{-1} under ECw of 0.25 dS m^{-1} and ARZT; 26.16 and 48.55 g bunch^{-1} under ECw of 6.50 dS m^{-1} and ARZT; 46.72 and 87.68 g bunch^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 2ºC; 14.76 and 30.00 g bunch^{-1} under ECw of 0.25 dS m^{-1} and ARZT + 4ºC; 8.70 and 24.90 g bunch^{-1} under ECw of 6.50 dS m^{-1} and ARZT + 4ºC.





In Figures A, B, E, and F, the lowercase letters compare the means of RZT levels within each ECw level and uppercase letters compare the means of ECw levels within each RZT level, according to Tukey's test ($p \leq 0.05$); **, * – significant at $p \leq 0.01$ and $p \leq 0.05$, respectively, according to Student's t-test; vertical bars indicate the means ± standard deviation.

Figure 7: Shoot fresh matter of the plant – SFM_{plant} (A-D) and SFM of the bunch of plants – SFM_{bunch} (E-H) of the coriander grown in an NFT hydroponic system.

Discussion

Numerous studies have been performed involving brackish water-use strategies under hydroponic conditions (Oliveira et al., 2023b; Silva et al., 2023bfg), including coriander (Silva et al., 2015; Silva et al., 2016a; Silva et al., 2018a; Bezerra et al., 2022; Santos Júnior et al., 2023; Silva et al., 2023a). Additionally, plants cultivated in uncontrolled environments are frequently exposed to different abiotic stresses, such as root-zone temperature (RZT). Other studies have subjected coriander to the isolated effect of RZTs (Nguyen et al., 2019; Nguyen et al., 2020) or combined with salt stress (Silva et al., 2020b; Silva et al., 2022).

The yield potential of hydroponic cultivation using brackish waters is evident, and such an improved plant response to salinity depends on several factors, such as the level of electrical conductivity of water (ECw) (Cazuza Neto et al., 2014; Silva et al., 2016a; Silva et al., 2018a), composition of salts present in the water (Bezerra et al., 2022), time of exposure to salt stress (Silva et al., 2015; Silva et al., 2022), and crop season (Silva et al., 2020b; Silva et al., 2022), among others.

Unlike other leafy vegetables, coriander is commercialized in fresh matter bunches, as it is sown with a certain number of seeds per cultivation unit in hydroponic cultivation (Santos Júnior et al., 2015; Cavalcante et al., 2016; Silva et al., 2016b; Santos Júnior et al., 2023; Silva et al., 2023d). Therefore, increasing the number of seeds per bunch may compensate for possible yield losses from cultivation conditions under isolated and/or combined effects of salinity and RZTs. For instance, other studies with coriander have formed bunches with 24 (Silva et al., 2015), 12 (Silva et al., 2016a; Silva et al., 2018a; Silva et al., 2020ab; Silva et al., 2022; Silva et al., 2023e), 10 (Bezerra et al., 2022), 15 (Navarro et al., 2022), and eight (Silva et al., 2023b) plants.

Experiments I (Figures 4D, 4G, 4H, 4J, 4L, and 4M) and II (Figures 6D, 6G, 6H, 6K, and 6L) recorded individual losses in stem diameter (SD), the number of leaves (NL), and leaf area (LA) as plant density per coriander bunch increased, causing losses in plant biomass production (Figures 5C, 5D, 7C, and 7D). Other studies have reported similar behavior with coriander (Moosavi et al., 2013; Silva et al., 2016b; Soares et al., 2017). However, the increase in plant density per bunch compensated for these individual losses, as expected, thus increasing the bunch biomass production (Figures 5E-H and 7E-H).

Coriander yield was notably different in the two experiments performed in the summer (Experiment I) and spring (Experiment II). For instance, the control treatments provided a mean shoot fresh matter of the bunch (SFM_{bunch}) of 2-fold at 20 days after transplanting (DAT) and 2.2-fold at 25 DAT, with a lower value in Experiment I (ECw 0.25 dS m^{-1}, Figures 5E and 5F) than Experiment II (ARZT of 28.80ºC and ECw 0.25 dS m^{-1}, Figures 7E and 7F), regardless of plant density. The SFM_{bunch} at 20 DAT in Experiment II (42.16 and 75.83 g $bunch^{-1}$) is comparable to those at 25 DAT in Experiment I (46.97 and 79.66 g $bunch^{-1}$), at densities of 6 and 30 plants, respectively. For comparison purposes, the study by Silva et al. (2020b) with Verdão coriander grown in an nutrient film technique (NFT) hydroponic system for 25 days recorded SFM_{bunch} yields of 75.98 and 79.72 g $bunch^{-1}$ with 12 plants. The tests occurred in the summer (ARZT of ~28ºC and ECw 0.30 dS m^{-1}) and autumn/winter (ARZT of ~24ºC and ECw 0.30 dS m^{-1}).

Previous studies have demonstrated the possibility of harvesting coriander at 20 DAT for commercialization (Silva et al., 2018a; Silva et al., 2020; Silva et al., 2022b; Silva et al., 2023e). In this sense, maintaining plants in the hydroponic system for a few more days is another strategy to compensate for production losses due to isolated and/or combined effects of salinity and RZTs. SFM_{bunch} production in Experiment I for T7 (ECw 6.50 dS m^{-1} with NaCl + $CaCl_2$ + KCl – equivalent 7:2:1 ratio) at 25 DAT (46.42 g $bunch^{-1}$) (Figure 5F) had the same magnitude of T1 when harvesting five days earlier (20 DAT) (47.22 g $bunch^{-1}$) (Figure 5E), and both bunches were formed with 30 plants. As expected, the highest density of 30 plants $bunch^{-1}$ compensated for losses due to salt stress. For instance, the production at 25 DAT for T7 had the same magnitude of T1 (46.97 g $bunch^{-1}$ with 6 plants). Also, similar productions occurred for T3 (ECw 6.50 dS m^{-1} with KCl), T5 (ECw 6.50 dS m^{-1} with $CaCl_2$), and T6 (ECw 6.50 dS m^{-1} with NaCl + $CaCl_2$ + $MgCl_2$ – equivalent 7:2:1 ratio), with approximately 40 g $bunch^{-1}$ with 30 plants. Although T4 (ECw 6.50 dS m^{-1} with $MgCl_2$, 26.18 g $bunch^{-1}$) and T2 (ECw 6.50 dS m^{-1} with NaCl, 34.06 g $bunch^{-1}$) had lower yields at the density of 30 plants, they showed the same magnitude of T1 at 20 DAT at densities of up to 24 plants. That reinforces the strategy of maintaining plants longer in the hydroponic system for biomass gains.

Most saline waters in studies with coriander were artificially produced by dissolving NaCl (Cazuza Neto et al., 2014; Silva et al., 2015; Silva et al., 2016a; Silva et al., 2018a; Silva et al., 2020b; Silva et al., 2022), and others used salts, such as KCl, $MgCl_2$, and $CaCl_2$, besides NaCl (Ahmadi and Souri, 2018; Bezerra et al., 2022; Navarro et al., 2022). Some studies have used naturally occurring brackish waters from wells with different cationic natures (Na^+, Ca^{2+}, and Mg^{2+}). An assay conducted in the Poço do Boi community, Ibimirim – PE/Brazil, used water with an EC of 1.70 dS m^{-1} (Santos et al., 2010). The Na^+ concentration in this water was 2.4- and 2.5-fold higher than Ca^{2+} and Mg^{2+}, respectively. The study by Silva et al. (2018b) in Cruz das Almas – BA/Brazil showed Na^+ concentrations of 0.73- and 2.17-fold and 0.41- and 1.26-fold higher than Ca^{2+} and Mg^{2+}, using water with an EC of 2.51 dS m^{-1} (from the Brito community in Sapeaçu – BA/Brazil) and 7.62 dS m^{-1} (from the Ipiranga community in Conceição do Coité – BA/Brazil), respectively. Both studies were conducted with lettuce under hydroponic conditions. Therefore, using water with a high EC level does not necessarily harm plant growth under hydroponic conditions, with a potential benefit from the mineral nutrients available in these waters.

In summary, using $MgCl_2$ in Experiment I to prepare saline water (ECw 6.50 dS m^{-1}) provided higher coriander production losses, even at higher plant densities per bunch (Figures 5E-H). As with other plant species (Martins et al., 2019b; Cruz et al., 2021), coriander's response to salt stress depends on the composition of salts in the water used for preparing nutrient solutions. A study by Bezerra et al. (2022) using an NFT hydroponic system and subjecting coriander to EC levels of nutrient solutions (ECsol 3.0, 4.5, and 6.0 dS m^{-1}) prepared in salinized water with NaCl, $MgCl_2$, and $CaCl_2$, fresh matter losses were lower when waters were salinized with NaCl or $CaCl_2$ salts instead of the NaCl + $CaCl_2$ + $MgCl_2$ mixture (in an equivalent 2:1:1 ratio).

Navarro et al. (2022) studied coriander in an deep flow technique (DFT) hydroponic system in tubes, and yield losses varied with the ECw levels used for preparing nutrient solutions besides salt types. These authors recorded higher fresh matter yields using NaCl or $MgCl_2$ than $CaCl_2$ to produce water with an EC of 1.72 or 3.32 dS m^{-1}. The productions were at the same level for water with an EC of 4.92 dS m^{-1} regardless of the salt (NaCl, $MgCl_2$, or $CaCl_2$).

Brackish water (ECw 6.50 dS m^{-1}) was produced only with NaCl in Experiment II, evidencing coriander yield differences between the two experiments. For instance, the maximum SFM_{bunch} production (34.06 g $bunch^{-1}$ with 30 plants) in Experiment I, obtained with T2 (ECw 6.50 dS m^{-1} with NaCl) at 25 DAT (Figure 5F), was lower than the values in Experiment II at the densities of 18, 24, and 30 plants (41.39, 44.27, and 45.54 g $bunch^{-1}$, respectively), cultivated under ambient conditions with ARZT of 28.80°C (Figure 7F). Such values have the same magnitude as five days earlier (20 DAT) without saline stress and the density of 6 plants (42.16 g $bunch^{-1}$) (Figure 7E). Therefore, maintaining plants longer in the hydroponic system for biomass gains is necessary to compensate for expected losses due to salt stress, besides increasing the number of plants per bunch.

In a similar study, Santos Júnior et al. (2023) sowed Tabocas coriander at densities of 1.0, 1.5, and 2.0 g of seeds $bunch^{-1}$ and four ECsol levels (1.49 dS m^{-1} – control without salt stress, 3.14, 4.87, and 6.44 dS m^{-1} prepared by mixing brackish water of a reservoir with rainwater). Brackish water had an ECw level of 9.93 dS m^{-1}. Coriander grew in the winter under a DFT hydroponic system in tubes. No biomass was lost with the increase in ECsol at a higher density, with means of 36.1 and 47.0 g bunch^{-1} at 28 and 35 days after sowing (DAS). These values show the same magnitude as those without saline stress at densities of 1.0 and 1.5 g of seeds - 36.81 and 39.04 g bunch^{-1} and 48.07 and 52.84 g bunch^{-1}, respectively.

As mentioned, maintaining plants longer in the hydroponic system and increasing the number of plants per bunch is necessary for biomass gains under stress conditions. In this case, the means of SFM_{bunch} at 25 DAT (Figures 7F and 7H) under combined stresses (ECw 6.50 dS m^{-1} and 30.64°C – ARZT + 2°C) and at the densities of 18, 24, and 30 plants had the same magnitude as those without salt stress at the density of 6 plants bunch^{-1} at 20 DAT (Figures 7E and 7G).

Coriander yield drastically reduced when cultivated with an increment of 4°C (ARZT + 4°C – mean of 32.59°C), regardless of cultivation conditions with or without saline stress (Figures 7E-H). The maximum SFM_{bunch} production at 25 DAT (28.76 g bunch^{-1} with 30 plants) under combined stresses (ECw 6.50 dS m^{-1} and ARZT of 32.59°C) had the same magnitude as those without saline stress at densities of 18, 24, and 30 plants (~27 g bunch^{-1}) (Figure 7F). The season in which Experiment II was conducted (spring) (Figure 1B) presented high nutrient solution temperatures in ambient conditions (ARZT of ~29ºC), similar to Experiment I performed in the summer (Figure 1A). Therefore, this extreme condition of combined stresses did not allow productions with commercialization characteristics (Figure 3F) even with a higher number of plants per bunch.

Other studies evaluating these combined stresses (RZTs and salinity) corroborate such findings. Silva et al. (2020b) found a more harmful effect on coriander in the summer, recording an SFM_{bunch} loss of Verdão coriander of approximately 55% under ECw of 6.50 dS m^{-1} and RZT of 30°C, compared to the control (ECw 0.30 dS m^{-1} and ARZT of ~28ºC). Another test conducted in the autumn/winter used the same stresses, recording an isolated effect response. SFM_{bunch} losses were approximately 17 and 49% relative to the respective controls (ARZT of ~24ºC and ECw 0.3 dS m^{-1}). A study by Silva et al. (2023f) grew endive and chicory under ECw of 5.50 dS m^{-1} and lettuce with 6.50 dS m^{-1} combined with ARZT + 6°C (corresponding to the mean temperatures of 30.73, 32.86, and 29.99°C). The experiments were performed in the autumn, winter/spring, and autumn/winter, respectively, confirming the cultivation viability of these leafy vegetables in such growing conditions.

In short, coriander response to isolated and/or combined salinity and RZT stresses depends on the growing season. Therefore, higher plant densities may not provide significant production gains of coriander bunches depending on the combined stress levels, as they strongly affect biomass production per plant and consequently of bunch. Coriander has shown a satisfactory response to RZT stress. Nguyen et al. (2020) observed in a DFT hydroponic system, minimal leaf fresh matter losses under an RZT of 30°C compared to the control (RZT of 25°C). Similarly, coriander can be grown with RZTs up to 32°C using NFT hydroponics but without saline water (Silva et al., 2020b).

Conclusions

The summer experiment using high-salinity water (ECw 6.50 dS m^{-1} with salts of different cationic natures, except for $MgCl_2$) allowed coriander growth, compensating for production losses due to the increased number of plants (density of 30 plants), with yields comparable to those without salt stress (ECw 0.25 dS m^{-1}) at the lowest density of 6 plants.

Using saline water with the same electrical conductivity level (ECw 6.50 dS m^{-1}) produced only with NaCl (spring experiment) also confirmed this compensation, as long as nutrient solution temperatures did not exceed 30.64°C.

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