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Hydroponic Cultivation of Laranja Cherry Tomatoes under Salt Stress and Foliar Application of Hydrogen Peroxide

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Abstract: The objective of this study was to evaluate the effect of the foliar application of hydrogen peroxide (H_2O_2) in mitigating the effects of salt stress on cherry tomato cultivation in a hydroponic system. The experiment was conducted in a greenhouse, using a Nutrient Film Technique hydroponic system. The experimental design used was completely randomized in a split-plot scheme, with four levels of electrical conductivity of the nutrient solution—ECns (2.1, 2.8, 3.5, and 4.2 dS m^{-1}), considered as plots, and five H_2O_2 concentrations (0, 12, 24, 36, and 48 µM), regarded as subplots, with four replicates and two plants per plot. An increase in the electrical conductivity of the nutrient solution negatively affected the production components of cherry tomatoes. However, it did not affect the post-harvest quality of the fruits. Despite the reductions observed in the production components due to the increase in the electrical conductivity of the nutrient solution, foliar application of H_2O_2 at concentrations esteemed between 22 and 25 µM attenuated the deleterious effects of salt stress on the number of fruits and ascorbic acid content and increased the total fruit production per plant of cherry tomatoes.

Keywords: *Solanum lycopersicum* L.; saline water; hydroponics; antioxidant substance

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Citation: Guedes, M.A.; Silva, A.A.R.d.; Lima, G.S.d.; Gheyi, H.R.; Soares, L.A.d.A.; Silva, L.d.A.; Oliveira, V.K.N.; Fátima, R.T.d.; Nobre, R.G.; Nóbrega, J.S.; et al. Hydroponic Cultivation of Laranja Cherry Tomatoes under Salt Stress and Foliar Application of Hydrogen Peroxide. *Agriculture* **2023**, *13*, 1688. https://doi.org/10.3390/agriculture13091688

Academic Editor: Athanasios Koukounaras

Received: 31 July 2023
Revised: 20 August 2023
Accepted: 23 August 2023
Published: 26 August 2023

1. Introduction

Cherry tomato (*Solanum lycopersicum* L.) is among the principal vegetables most cultivated in protected environments [1]. In recent years, its cultivation has increased worldwide, especially due to the added economic value and nutritional benefits [2]. Its fruits contain high levels of vitamin C and antioxidants [3], which favors its acceptance by consumers. In addition, cherry tomatoes also have a longer shelf life, which makes their commercialization more attractive [4].

Brazil is one of the largest tomato producers in the world, producing 3,679,160 tons in 2021 in an area of 51,907 hectares, which resulted in an average yield of 70.88 t ha^{-1}, with the Northeast region accounting for 14.72% (541,701 tons) of the national production, with a harvested area of 9989 ha and average yield of 54.23 t ha^{-1} [5], i.e., a reduction of 23.49% (16.65 t ha^{-1}) in yield compared to the national average.

The reduced yield in the Northeast region may be related to the limitations imposed by the salinity of groundwater used for agricultural cultivation. The semi-arid region of the Brazilian Northeast has low rainfall and high evaporation rates, which naturally contributes to water deficit and increased salt concentrations in water sources, negatively affecting the growth and development of crops [6,7].

The harmful effects caused by salt stress are related to the reduction in the availability of water and nutrients to plants and to the toxic effect of Na^+ and Cl^- [8,9]. Excess salts present in the water also induce osmotic stress, ionic toxicity, and secondary stress as oxidative stress, directly leading to reductions in fruit production and post-harvest quality [10–12].

In a study conducted by Roque et al. [13] to evaluate the effects of irrigation with brackish waters on the production of cherry tomatoes, reductions in the production components were observed when plants were irrigated using water with electrical conductivity above 0.3 dS m^{-1}, demonstrating the sensitivity of cherry tomatoes to salt stress. Batista et al. [14] evaluated the production of cherry tomato cultivars in hydroponic systems and also found reductions with increments in nutrient solution salinity above 2.5 dS m^{-1}. Martínez et al. [15], when evaluating the post-harvest quality of cherry tomatoes fruits under salt stress, observed an increase in the contents of total soluble solids, lycopene, and titratable acidity as a function of salt stress.

In recent years, the cultivation of vegetables in a protected environment using hydroponic systems has increased, mainly due to the improvements in nutrient and phytosanitary control [14,16,17]. Hydroponic cultivation reduces water consumption and the effects of salinity on plants due to the absence of matric potential [18], which favors cultivation in regions that face scarcity of water with low electrical conductivity.

Given the growing need to use brackish water in agriculture, especially in semi-arid regions, searching for strategies that enable such use has been a great challenge for the scientific community. Among the strategies, the use of hydrogen peroxide (H_2O_2) stands out because, when applied at appropriate concentrations, it can contribute to reducing the harmful effects of salinity and enable agricultural cultivation [19,20]. Hydrogen peroxide is a reactive oxygen species (ROS), which acts as a key signaling molecule in mediating physiological and metabolic processes, alleviating the adverse effects of stress on plants by increasing the activity of antioxidant enzymes and membrane stability, which in turn increases plant's tolerance to abiotic stresses [21,22].

In recent years, studies have reported that foliar application of H_2O_2 can attenuate the deleterious effects caused by salt stress on various vegetables, such as mini watermelon [18], bell peppers [23], melon [24], zucchini [25], and tomatoes [26]. However, it should be considered that the beneficial effects of H_2O_2 application depend on several factors, including concentration, plant species, development stage, and method of application [27,28].

This study is based on the hypothesis that the foliar application of H_2O_2 at adequate concentrations attenuates the harmful effects caused by nutrient solution salinity on the production components and post-harvest quality of fruits of cherry tomatoes, inducing their tolerance to salt stress using physiological and metabolic processes, increasing the activity of antioxidant enzymes. In this context, the objective of this study was to evaluate the effect of foliar application of H_2O_2 in mitigating the effects of salt stress on cherry tomatoes cultivated in a Nutrient Film Technique hydroponic system.

2. Materials and Methods

2.1. Experiment Location

The experiment was conducted in a semi-arid region of the Brazilian Northeast, in the municipality of Pombal, Paraíba, Brazil, situated by the geographic coordinates 6°46′13′′ S latitude, 37°48′6′′ W longitude W and at an average altitude of 184 m. The study was conducted in a greenhouse belonging to the Center of Science and Agri-Food Technology (CCTA) of the Federal University of Campina Grande (UFCG) from November 2022 to February 2023. The meteorological data of the experimental site are presented in Figure 1.

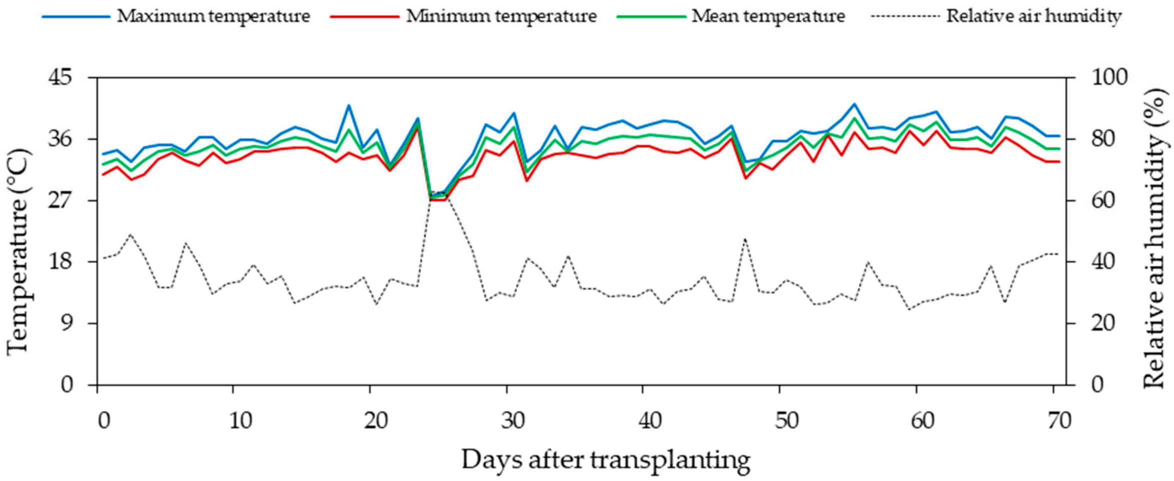

Figure 1. Maximum, minimum, and mean temperature and average relative air humidity observed inside the greenhouse during the experimental period.

2.2. Cultivar Studied

Seeds of 'Laranja' cherry tomatoes' from Topseed Garden® (Agristar-Santo Antônio de Posse, SP, Brazil) were used in the study. This cultivar has a cycle of around 90 days, plants of indeterminate growth habit, with excellent leaf structure and highly productive. The fruits have excellent post-harvest quality, with varying lengths and diameters between 20 and 25 mm. In addition, 'Laranja' cherry tomato is resistant to fusarium wilt and nematodes [29].

2.3. Treatments and Experimental Design

The treatments consisted of four levels of salinity of the nutrient solution—ECns (2.1 —control, 2.8, 3.5, and 4.2 dS m^{-1}) and five concentrations of hydrogen peroxide—H_2O_2 (0—control, 12, 24, 36, and 48 μM), distributed in a completely randomized design in a split-plot scheme, with nutrient solution salinity levels considered the plots and H_2O_2 concentrations considered the subplots, with three replicates and two plants per plot, totaling 120 experimental units.

The electrical conductivity levels of the nutrient solution were based on a study conducted by Silva et al. [18] with hydroponic mini watermelon (*Citrullus lanatus* L.), while the H_2O_2 concentrations were adapted from the study conducted by Dantas et al. [25] with zucchini (*Cucurbita pepo* L.).

2.4. Experiment Setup and Conduction

The procedures for installing and handling the nutrient solution were carried out in accordance with the research carried out by Mendonça et al. [17]. The arrangement of hydroponic profiles and distribution of plants in the experimental area are shown in Figure 2A,B.

The nutrient solution used in the research was prepared according to Hoagland and Arnon [30]. The fertilizers used as sources of macronutrients in the preparation of the solution were monobasic potassium phosphate (KH_2PO_4), potassium nitrate (KNO_3), calcium nitrate ($Ca(NO_3)_2 \cdot 4H_2O$), and magnesium sulfate ($MgSO_4 \cdot 7H_2O$). Boric acid (H_3BO_3), manganese sulfate ($MnSO_4 \cdot 4H_2O$), zinc sulfate ($ZnSO_4 \cdot 7H_2O$), copper sulfate ($CuSO_4 \cdot 5H_2O$), ammonium molybdate ($(NH_4)_6Mo_7O_{24} \cdot 4H_2O$), ferrous sulfate ($FeSO_4$), and EDTA-Na were used as source of micronutrients.

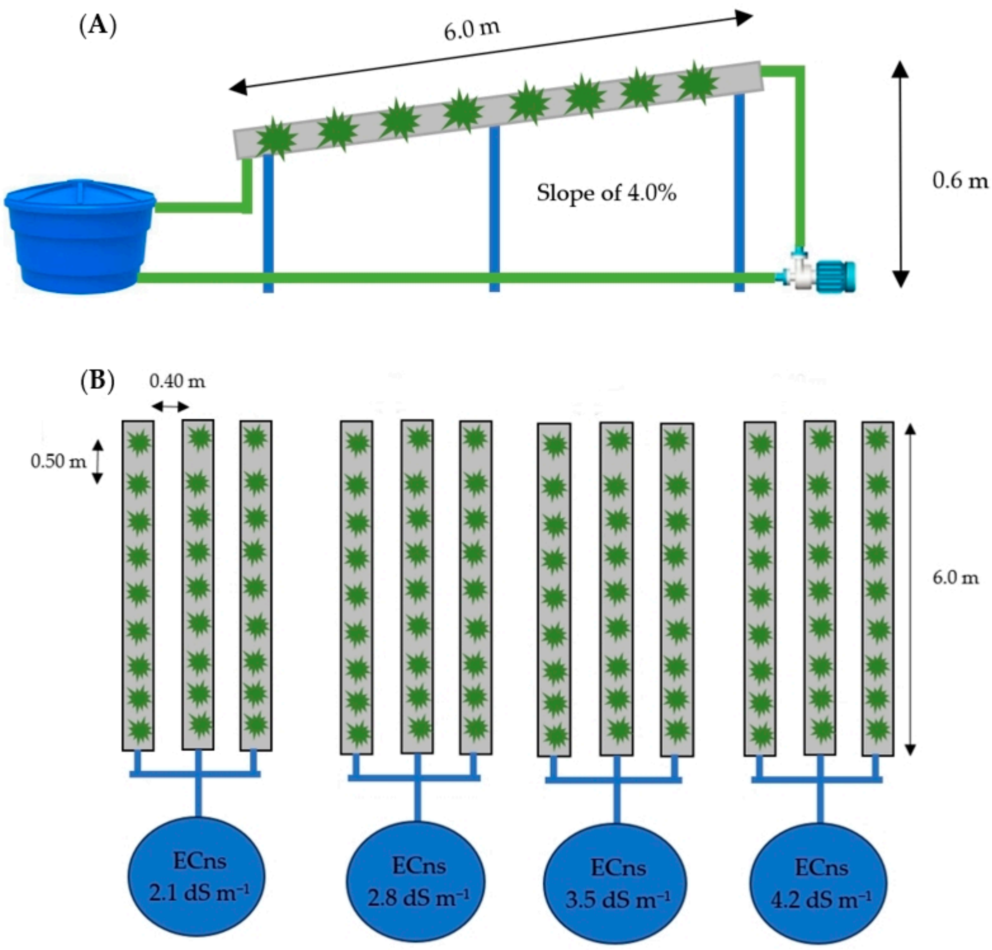

Figure 2. Side (**A**) and top (**B**) view details of hydroponic profiles.

Substrate preparation and seedling formation were carried out according to a study carried out by Mendonça et al. [17]. The proportion and preparation of salinity levels of the nutrient solution were carried out according to Oliveira et al. [11].

The complete replacement of the nutrient solution occurred every eight days; however, the electrical conductivity and pH were monitored daily, and whenever necessary, the solution was adjusted by adding public-supply water with ECw of 0.3 dS m^{-1} or 100% nutrient solution as the case may be, always maintaining the ECns according to the established treatments. The pH was maintained between 5.5 and 6.5 by the addition of 0.1 M potassium hydroxide (KOH) or hydrochloric acid (HCl). The plants were grown using vertical support fixed with a plastic string (number 10) (Figure 3).

Applications of H_2O_2 were performed via foliar spraying between 17:00 and 18:00 h. The first application was carried out five days before the beginning of the application of the different levels of ECns (8 DAT), and the subsequent ones were performed at 12-day intervals. Hydrogen peroxide applications were interrupted after the appearance of the fruits (35 DAT, totaling three H_2O_2 applications). The average volume applied in each application per plant was 19 mL. The applications were carried out manually, with a sprayer to completely wet the leaves (abaxial and adaxial sides). During H_2O_2 spraying, a structure with plastic tarpaulin was used to prevent the solution from drifting onto neighboring plants.

(**A**) (**B**) (**C**)

Figure 3. Cultivation of 'Laranja' cherry tomatoes in Nutrient Film Technique—NFT hydroponic system in different phenological stages of development (Vegetative growth—(**A**), Fruiting stage—(**B**) e Fruiting and ripening stage—(**C**)).

2.5. Traits Analyzed

2.5.1. Production Variables

The fruits began to be harvested at 40 DAT when they showed an orange color, characteristic of ripe fruits, and the harvest process extended to 70 DAT when the following traits were determined: number of fruits per plant (NFP); average fruit weight (AFW—g per fruit); total fruit production per plant (TPP—g per plant); fruit polar diameter (FPD—mm), and fruit equatorial diameter (FED—mm). Polar and equatorial diameters were obtained with a digital caliper.

2.5.2. Post-Harvest Quality Variables

Soon after harvesting, the cherry tomatoes were washed in drinking water to remove impurities from the fruits and then dried at ambient temperature to remove the excess water on the surface of the fruits. The post-harvest analyses were performed using fresh fruits via the determination of hydrogen potential—pH, electrical conductivity—EC, ascorbic acid—AA (mg 100 g^{-1} of pulp), soluble solids—SS (°Brix), total sugars—SU (%), titratable acidity—TA (%), moisture—MOIST (%), ashes—ASH (%), and fibers—FIB (%).

The pH was determined directly in the pulp immediately after harvest, with a digital pH meter (COMBO5, AKSO, São Leopoldo, RS, Brazil) previously calibrated at pH 7.0 with buffer solution and electrical conductivity was measured using a benchtop conductivity meter (Q795A, Quimis®, Diadema, SP, Brazil); soluble solids (°Brix) were measured by direct reading in a digital refractometer (MA871, AKSO®, São Leopoldo, RS, Brazil); and ascorbic acid content (mg 100 g^{-1} of pulp) was determined using titration. The determinations were performed using the methodologies by [31]. Titratable acidity, total sugars, moisture, ash, and fiber were determined according to [31] standard methods and expressed as a percentage.

2.6. Statistical Analysis

The collected data were subjected to the distribution normality test (Shapiro–Wilk) at a 0.05 probability level. Then, analysis of variance was performed at a 0.05 probability level, and in the cases of significance, regression analysis was performed using the statistical software SISVAR-ESAL [32].

3. Results

There was a significant interaction ($p \leq 0.01$) between nutrient solution salinity and H_2O_2 concentrations only for the number of fruits per plant (Table 1). The salinity levels of the nutrient solution significantly influenced all the variables of the production components analyzed. Hydrogen peroxide concentrations significantly ($p \leq 0.01$) affected the number of fruits per plant and the total production per plant.

Table 1. Summary of the analysis of variance for the number of fruits per plant (NFP), total production per plant (TPP), average fruit weight (AFW), fruit polar diameter (FPD), and fruit equatorial diameter (FED) of cherry tomatoes grown using saline nutrient solution and foliar application of hydrogen peroxide in a hydroponic system, in the harvests performed from 40 to 70 days after transplantation.

Source of Variation	DF	Mean Squares				
		NFP	TPP	AFW	FPD	FED
Saline nutrient solution (ECns)	3	1413.60 **	172,330.59 **	12.68 **	23.16 **	56.28 **
Linear regression	1	4093.03 **	498,323.61 **	35.09 **	69.25 **	158.82 **
Quadratic regression	1	63.76 *	289.61 ^{ns}	1.92 ^{ns}	0.12 ^{ns}	3.37 ^{ns}
Residual 1	6	4.41	960.69	0.19	1.57	2.17
Hydrogen peroxide (H_2O_2)	4	387.52 **	11,312.80 **	0.63 ^{ns}	4.69 ^{ns}	6.69 ^{ns}
Linear regression	1	55.97 ^{ns}	1151.65 ^{ns}	0.02 ^{ns}	0.78 ^{ns}	8.11 ^{ns}
Quadratic regression	1	1298.93 **	39,417.44 **	0.22 ^{ns}	0.52 ^{ns}	13.31 ^{ns}
Interaction (ECns × H_2O_2)	12	68.89 **	2763.34 ^{ns}	0.48 ^{ns}	1.15 ^{ns}	1.16 ^{ns}
Residual 2	34	22.27	689.10	0.49	1.23	1.42
CV 1 (%)		4.44	7.27	5.41	5.09	6.35
CV 2 (%)		9.97	6.16	8.65	4.50	5.13

ns, *, and **, respectively not significant, significant at a $p \leq 0.05$ and $p \leq 0.01$. DF: Degrees of freedom, CV: Coefficient of variation.

Foliar application of H_2O_2 with concentrations up to 23 µM promoted an increase in the number of fruits per plant (Figure 4A), even when the plants were subjected to the highest ECns level (4.2 dS m^{-1}). The highest NFP (63.87 fruits per plant) was obtained in plants grown with ECns of 2.1 dS m^{-1} at the H_2O_2 concentration of 23 µM, corresponding to an increase of 19.74% (10.53 fruits per plant) compared to plants grown with the same salinity level (2.1 dS m^{-1}) and without application of H_2O_2 (0 µM). However, foliar application of H_2O_2 at concentrations greater than 23 µM intensified the harmful effects of salt stress on the number of fruits per plant, with the lowest value (29.41 fruits per plant) observed in plants subjected to ECns of 4.2 dS m^{-1} and H_2O_2 concentration of 48 µM.

Average fruit weight (Figure 4B) and total production per plant (Figure 4C) were negatively affected by the increase in nutrient solution salinity, corresponding to reductions of 9.47% and 14.34%, respectively with per unit increment in ECns, i.e., cherry tomatoes grown under ECns of 4.2 had reductions of 24.83% (2.27 g per fruit) in AFW and 43.09% (235.54 g per plant) in TPP when compared to those subjected to ECns of 2.1 dS m^{-1}.

Hydrogen peroxide applied up to the concentration of 25 µM promoted an increase in the total production per plant (Figure 4D), with the highest value of TPP (456.95 g per plant) obtained in plants sprayed with the H_2O_2 concentration of 25 µM, i.e., an increase of 17.32% (67.47 g per plant) compared to those subjected to a concentration of 0 µM.

Nutrient solution salinity negatively affected the polar (Figure 5A) and equatorial (Figure 5B) diameter of cherry tomatoes, with reductions of 4.75% and 6.98%, respectively, with per unit increment in ECns. When comparing the FPD and FED of plants grown with ECns of 4.2 dS m^{-1} with the values of those subjected to ECns of 2.1 dS m^{-1}, reductions of 11.10% (2.88 mm) and 17.17% (4.36 mm) were observed, respectively.

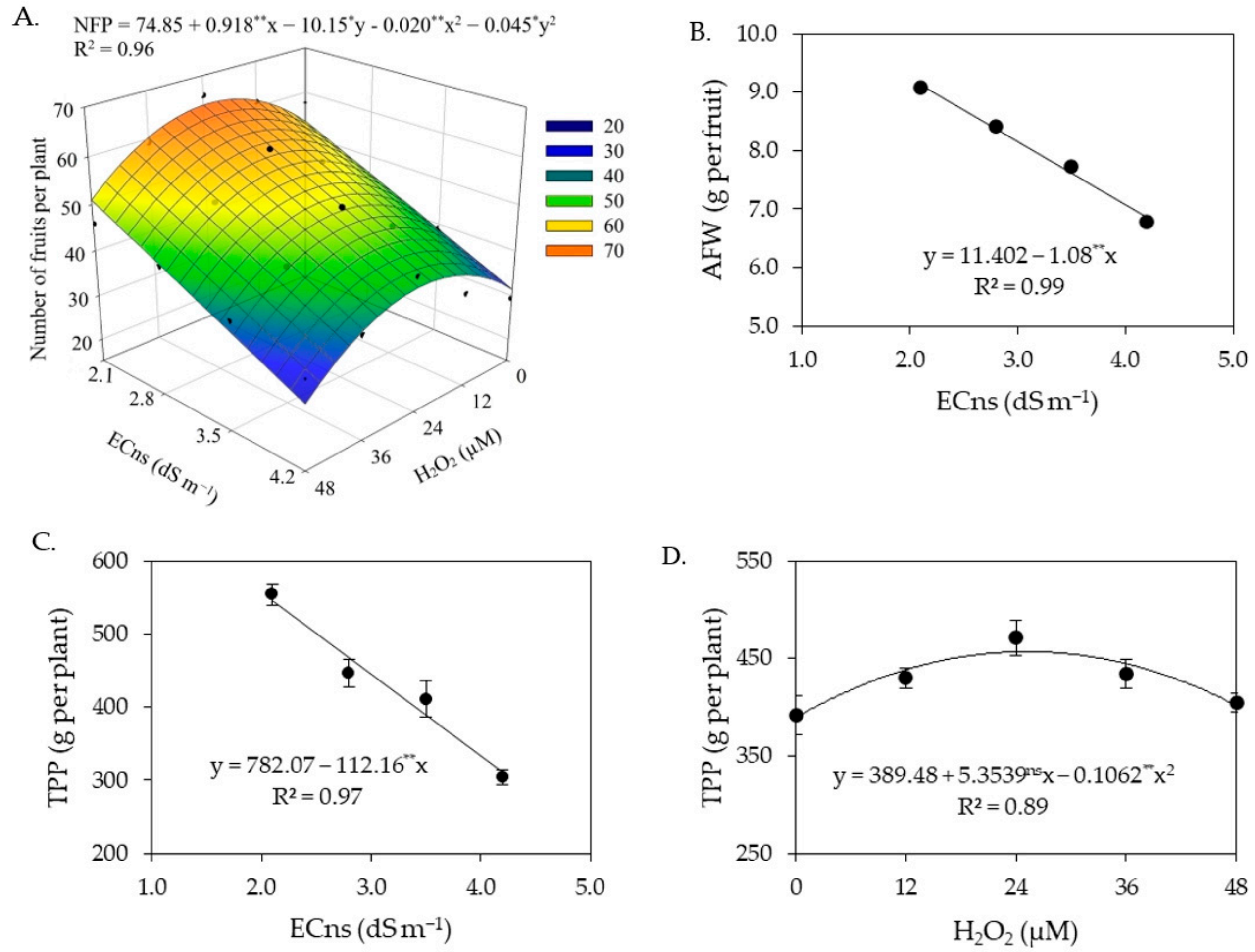

Figure 4. Number of fruits per plant-NFP (**A**) of cherry tomatoes as a function of the interaction between hydrogen peroxide concentrations and salinity levels of the nutrient solution-ECns, average fruit weight-AFW (**B**) as a function of ECns levels, and total production per plant-TPP as a function of ECns levels (**C**) and concentrations of hydrogen peroxide-H_2O_2 (**D**). X and Y-concentration of H_2O_2 and ECns, respectively; ns, *, and **, respectively not significant, significant at a $p \leq 0.05$ and $p \leq 0.01$. Vertical lines represent the standard error of the mean (n = 3).

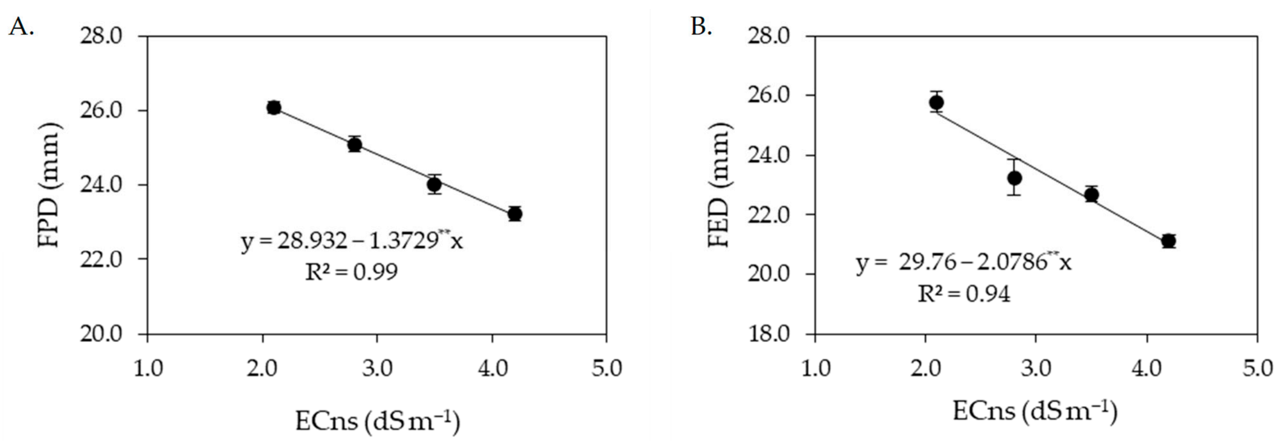

Figure 5. Polar (**A**) and equatorial (**B**) diameter of fruits of cherry tomato grown in a hydroponic system as a function of salinity levels of the nutrient solution—ECns, in the harvest performed from 40 to 70 days after transplantation. ** significant at a $p \leq 0.01$. Vertical lines represent the standard error of the mean (n = 3).

The interaction between salinity levels of the nutrient solution and concentrations of hydrogen peroxide (ECns × H_2O_2) significantly ($p \leq 0.01$) influenced the contents of ascorbic acid (AA) and soluble solids (SS) of cherry tomatoes (Table 2). The salinity levels of the nutrient solution, when considered individually, significantly ($p \leq 0.01$) influenced all traits except moisture (MOIST). Hydrogen peroxide concentrations significantly affected the variables AA, SS, and TA.

Table 2. Summary of the analysis of variance for hydrogen potential (pH), ascorbic acid (AA), soluble solids (SS), titratable acidity (TA), and moisture (MOIST) in fruits of cherry tomatoes grown in a hydroponic system with saline nutrient solution and foliar application of hydrogen peroxide.

Source of Variation	**DF**	**Mean Squares**				
		pH	**AA**	**SS**	**TA**	**MOIST**
Saline nutrient solution (ECns)	3	0.11 **	7.01 **	3.39 **	15.25 **	3.76 ns
Linear regression	1	0.31 **	6.62 *	9.75 **	45.53 **	1.01 ns
Quadratic regression	1	0.01 ns	13.95 **	0.22 ns	0.01 ns	5.22 ns
Residual 1	6	0.003	0.14	0.004	0.04	1.35
Hydrogen peroxide (H_2O_2)	4	0.01 ns	6.99 **	0.15 **	1.35 **	1.69 ns
Linear regression	1	0.03 ns	3.56 *	0.61 **	5.30 **	0.32 ns
Quadratic regression	1	0.01 ns	11.87 **	0.01 ns	0.01 ns	6.16 ns
Interaction (ECns × H_2O_2)	12	0.01 ns	7.18 **	0.03 **	0.13 ns	2.09 ns
Residual 2	34	0.004	0.10	0.002	0.05	1.92
CV 1 (%)		1.51	6.56	2.30	1.93	1.24
CV 2 (%)		1.65	5.68	1.96	2.16	1.47

ns, *, and **, respectively not significant, significant at a $p \leq 0.05$ and $p \leq 0.01$. DF: Degrees of freedom, CV: Coefficient of variation.

The pH (Figure 6A) and titratable acidity (Figure 6B) of cherry tomato pulp increased by 2.84% (pH) and 14.56% (TA) per unit increment in ECns. Cherry tomato plants grown with ECns of 4.2 dS m^{-1} increased pH by 5.66% (0.22) and titratable acidity by 23.51% (0.12) compared to plants grown under ECns of 2.1 dS m^{-1}. The increase in H_2O_2 concentrations also promoted an increase in titratable acidity (Figure 6C), with the highest TA value (0.511%) obtained in plants sprayed with the H_2O_2 concentration of 48 µM and the lowest value (0.423%) in the control plants, i.e., those that did not receive an application of H_2O_2 (0 µM).

Foliar application of H_2O_2 at a concentration of 22 µM promoted an increase in the ascorbic acid content (Figure 7A) in the pulp of cherry tomatoes, with the highest value (6.38 mg 100 g^{-1} of pulp) observed in plants grown with ECns of 2.8 dS m^{-1}, while the pulp of the fruits subjected to the same ECns level but without application of H_2O_2 (under concentration of 0 µM) recorded a reduction of 2.51% (0.16 mg 100 g^{-1} of pulp).

The increase in the salinity of the nutrient solution had an increasing linear effect on the soluble solids of cherry tomato pulp (Figure 7B), regardless of the H_2O_2 concentration. Plants grown with ECns of 4.2 dS m^{-1} and sprayed with the H_2O_2 concentration of 48 µM stood out with the highest SS value (5.92 °Brix), corresponding to an increase of 4.78% (0.27 °Brix) compared to plants grown under ECns of 4.2 dS m^{-1} and without application of H_2O_2 (0 µM). On the other hand, the lowest SS value (4.61 °Brix) was recorded in plants grown with ECns of 2.1 dS m^{-1} under the H_2O_2 concentration of 0 µM.

The salinity levels of the nutrient solution and the concentrations of H_2O_2, analyzed alone or via interaction, significantly ($p \leq 0.01$) affected only the content of the total sugars of cherry tomatoes (Table 3).

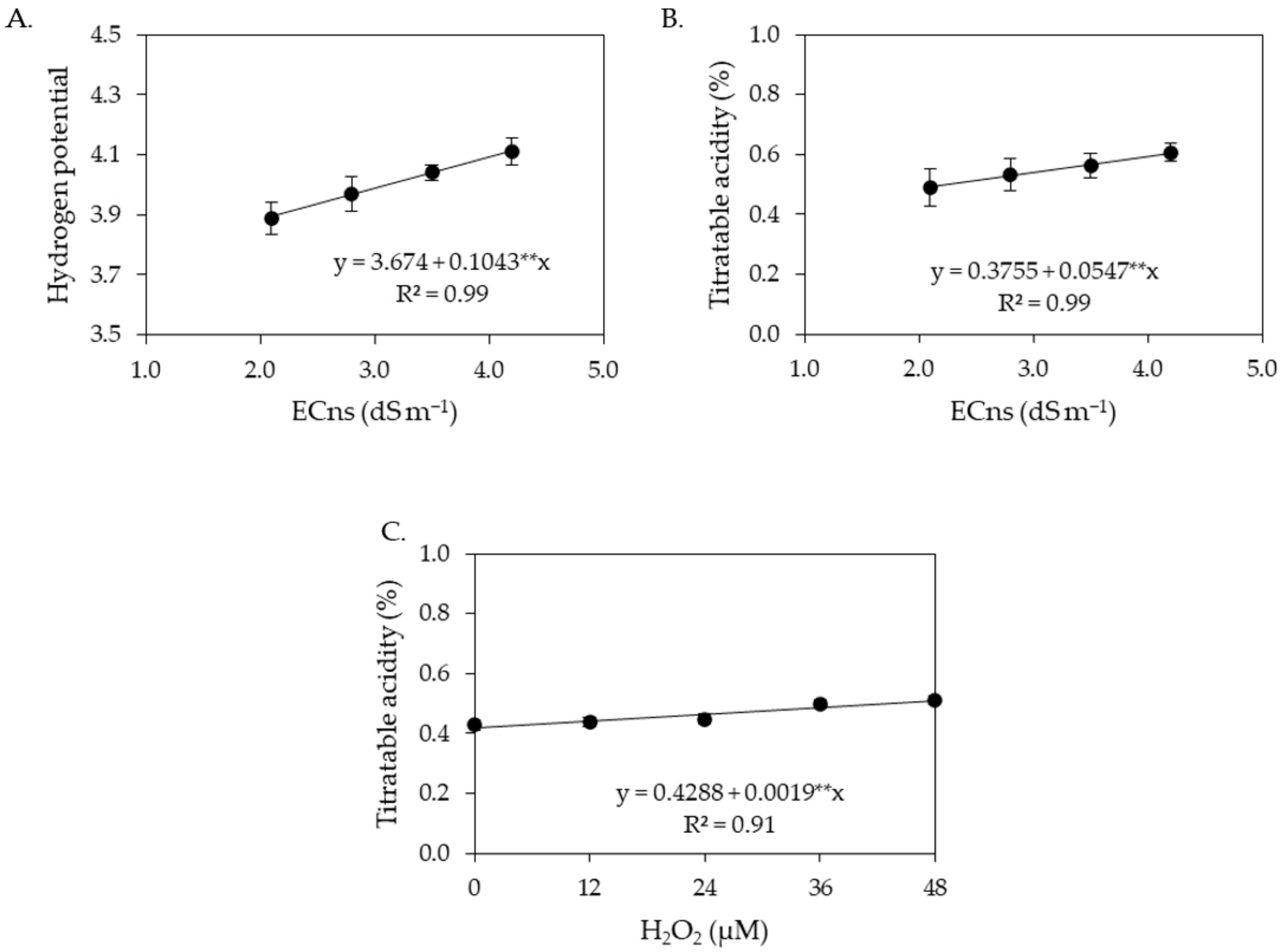

Figure 6. Hydrogen potential-pH (**A**) and titratable acidity-TA (**B**) of cherry tomato pulp as a function of salinity of the nutrient solution, and titratable acidity-TA (**C**) as a function of hydrogen peroxide concentrations (H_2O_2) at 70 days after transplantation. ** significant at a $p \leq 0.01$. Vertical lines represent the standard error of the mean (n = 3).

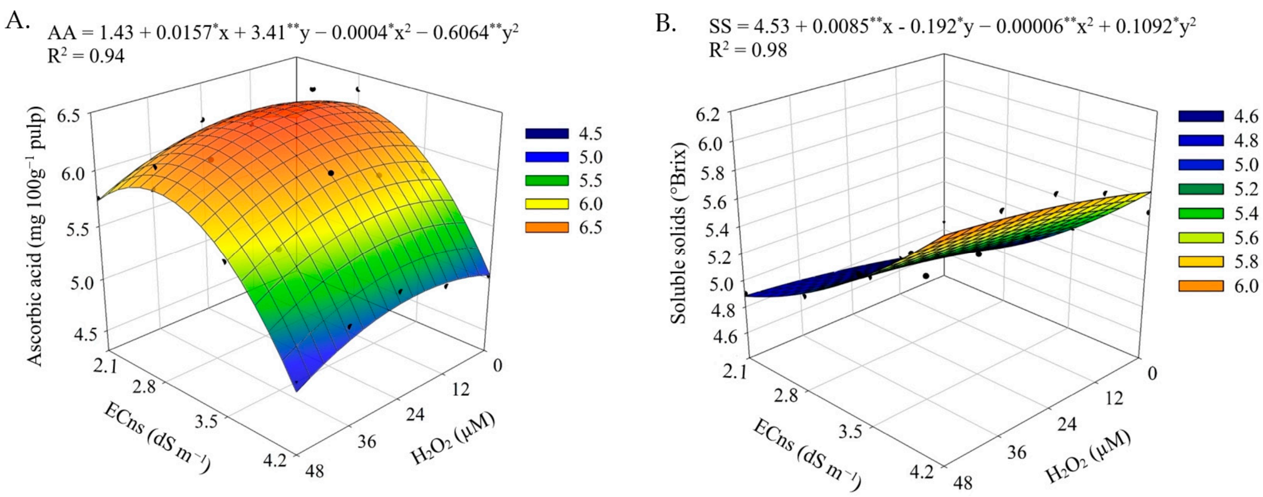

Figure 7. Ascorbic acid–AA (**A**) and soluble solids–SS (**B**) of cherry tomato pulp as a function of the interaction between salinity of the nutrient solution (ECns) and hydrogen peroxide concentrations (H_2O_2). X and Y-concentration of H_2O_2 and ECns, respectively; * and ** significant at $p \leq 0.05$ and $p \leq 0.01$, respectively. Vertical lines represent the standard error of the mean (n = 3).

Table 3. Summary of the analysis of variance for ashes (ASH), fibers (FIB), electrical conductivity (EC), and the total sugars (SU) in fruits of cherry tomatoes, grown in a hydroponic system with saline nutrient solution and foliar application of hydrogen peroxide.

Source of Variation	DF	Mean Squares			
		ASH	FIB	EC	SU
Saline nutrient solution (ECns)	3	0.19 ^{ns}	1.92 ^{ns}	4641.30 ^{ns}	730.05 **
Linear regression	1	0.20 ^{ns}	0.21 ^{ns}	765.63 ^{ns}	2153.66 **
Quadratic regression	1	0.13 ^{ns}	1.23 ^{ns}	10,662.93 ^{ns}	15.61 ^{ns}
Residual 1	6	0.03	0.45	2607.54	0.21
Hydrogen peroxide (H_2O_2)	4	0.04 ^{ns}	0.73 ^{ns}	2960.55 ^{ns}	42.54 **
Linear regression	1	0.03 ^{ns}	2.50 ^{ns}	6072.21 ^{ns}	168.84 **
Quadratic regression	1	0.01 ^{ns}	0.35 ^{ns}	2900.36 ^{ns}	0.40 ^{ns}
Interaction (ECns × H_2O_2)	12	0.09 ^{ns}	0.64 ^{ns}	2468.51 ^{ns}	1.92 **
Residual 2	34	0.06	0.34	2476.38	0.27
CV 1 (%)		19.20	28.49	13.91	1.23
CV 2 (%)		23.47	20.47	13.56	1.38

ns and **, respectively not significant, significant at a $p \leq 0.05$ and $p \leq 0.01$. DF: Degrees of freedom, CV: Coefficient of variation.

Foliar spraying of H_2O_2 at a concentration of 25 µM associated with nutrient solution salinity of 4.2 dS m^{-1} promoted the highest value of total sugars (46.75%) in cherry tomato pulp (Figure 8). On the other hand, plants grown under ECns of 2.1 dS m^{-1} and without application of H_2O_2 (0 µM) presented the lowest value of total sugars (27.91%).

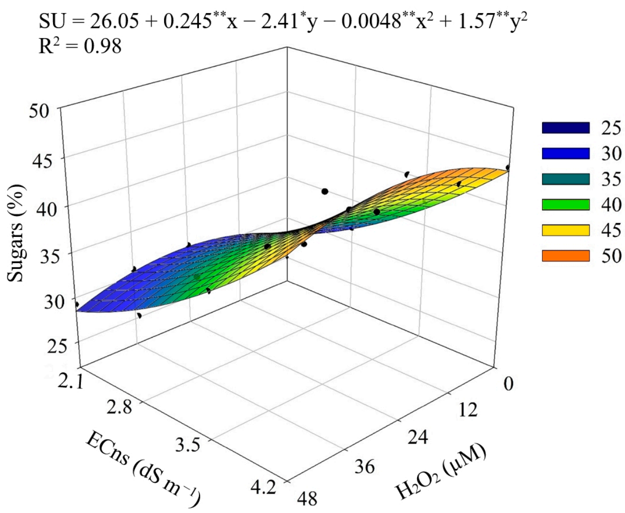

Figure 8. Content of total sugars of cherry tomato pulp as a function of the interaction between nutrient solution salinity (ECns) and hydrogen peroxide concentrations (H_2O_2). X and Y-concentration of H_2O_2 and ECns, respectively; * and ** significant at a $p \leq 0.05$ and $p \leq 0.01$, respectively. Vertical lines represent the standard error of the mean (n = 3).

4. Discussion

Salinity has posed a serious threat to crop production and yields [33], especially in arid and semi-arid regions. Salt stress causes damage to plants and induces disturbances in physiological and metabolic processes, negatively affecting food production [34]. The results of the present study show that salt stress caused by the increase in the electrical conductivity of the nutrient solution negatively affected the production components of cherry tomatoes. However, foliar application of H_2O_2 at concentrations between 22 and 25 µM mitigates the effect of salt stress on the number of fruits (Figure 4A) and increases total production per plant (Figure 4D).

The reduction in the number of fruits per plant (NFP) of cherry tomatoes may be related to water stress induced by salinity and nutritional imbalance caused by the high absorption of ions, mainly sodium (Na^+) and chloride (Cl^-) [35]. Reductions in the number of fruits per plant caused by salinity were also observed by Roque et al. [13], who evaluated gas exchange and production of cherry tomatoes under salt stress (ECw ranging from 0.3 to 4.3 dS m^{-1}) in conventional cultivation and found a decrease of 38.9% comparing plants irrigated with ECw of 0.3 dS m^{-1} to those cultivated with ECw of 4.3 dS m^{-1}.

On the other hand, the beneficial effect of H_2O_2 at the concentration of 23 μM on NFP may be associated with its function of signaling molecule and protection against biotic and abiotic stresses [36]. Hydrogen peroxide can activate the defense system, contributing to a rapid adaptation of the plant to conditions unfavorable to its development [20,28].

It is worth pointing out that, at concentrations greater than 23 μM, H_2O_2 intensified the effects of salt stress on the number of fruits (Figure 4A). Hydrogen peroxide is the most stable reactive oxygen species and can diffuse rapidly across the subcellular membrane [37]. As reported by Veloso et al. [38], at high concentrations, H_2O_2 can cause damage to plants, possibly due to the changes that occur in their metabolism, mainly as a consequence of oxidative stress.

The increase in the electrical conductivity of the nutrient solution also reduced the average fruit weight (Figure 3B) and the total production per plant (Figure 4C) of cherry tomatoes. Under salt stress conditions, a systemic decrease in energy occurs due to reductions in photosynthetic rate and leaf area, as well as by its redistribution to defense and tolerance mechanisms [39,40]. The harmful effects of salinity extend to the cellular level, causing membrane damage, increased production of reactive oxygen species, and reduced enzymatic activity [41], and all of these disorders act to reduce the production components.

Batista et al. [14] conducted a study to evaluate the physiology and production of cherry tomatoes cultivars (Samambaia, Tomate Vermelho, and Caroline) under salt stress (ECns ranging from 2.5 to 8.5 dS m^{-1}) in an NFT hydroponic system and found a decrease in the total production per plant as ECns increased, with reductions of 42.78% (182.70 g) in the cultivar Samambaia, 74.14% (288.34 g) in Tomate Vermelho, and 57.17% (144.4 g) in Caroline, when comparing plants subjected to ECns of 8.5 dS m^{-1} with those grown under ECns of 2.5 dS m^{-1}.

Foliar application of H_2O_2 up to a concentration of 25 μM promoted an increase in the total production per plant of cherry tomatoes (Figure 4D). The beneficial effects of H_2O_2 on TPP may be related to the activity of enzymes involved in glycolysis and energy metabolism, which increase the production of ATP necessary for plant growth and development [9]. Hydrogen peroxide, when applied at appropriate concentrations, contributes to the accumulation of inorganic and organic solutes [42,43].

The polar (Figure 5A) and equatorial (Figure 5B) diameters of cherry tomatoes were negatively affected by the increase in electrical conductivity of the nutrient solution. Silva et al. [1], when evaluating the growth and production of cherry tomatoes under salt stress (ECw ranging from 0.6 to 2.6 dS m^{-1}) in conventional cultivation, observed reductions of 4.54% in FPD and 2.52% in FED when comparing plants irrigated with the highest salinity (2.6 dS m^{-1}) to those cultivated with ECw of 0.6 dS m^{-1}. Excess salts present in the nutrient solution cause osmotic stress, negatively affecting the absorption of water and nutrients by plants [44], which may have resulted in reductions in FPD and FED observed in the present study.

The cherry tomato is a climacteric fruit, as its ripening can occur after harvest. Therefore, it has a relatively limited post-harvest life since many processes that affect quality occur after harvest [45]. The increase in the electrical conductivity of the nutrient solution promoted an increase in the pH (Figure 6A) of the fruit pulp. According to Tigist et al. [46], lower pH values are related to a slower respiration rate and better quality maintenance.

The fruits obtained in this study had pH values ranging between 3.89 and 4.11, which are considered ideal for tomatoes [47]. pH value below 4.5 is a desirable characteristic as it prevents the proliferation of microorganisms [46].

For titratable acidity, an increase was observed with the increase in the electrical conductivity of the nutrient solution (Figure 6B) and in the concentrations of H_2O_2 (Figure 5C). The values of titratable acidity found in this study were higher than the quality standards recommended for tomatoes [48], considering that values above 0.4% were obtained.

Ascorbic acid is one of the essential compounds with high antioxidant activity and one of the important indicators of fruit freshness [49]. Foliar spraying with H_2O_2 at a concentration of 22 μM was able to increase the ascorbic acid content in cherry tomato pulp (Figure 7A), even in plants grown with ECns of 4.2 dS m^{-1}. An increase in ascorbic acid content as a function of foliar application of H_2O_2 was also observed by Silva et al. [18] in hydroponic mini watermelon under salt stress (ECns ranging from 2.1 to 5.1 dS m^{-1}), as these authors found that foliar application H_2O_2 at a concentration of 20 μM promoted increase even in plants subjected to the highest level of salinity (5.1 dS m^{-1}).

An increase in the electrical conductivity of the nutrient solution associated with the foliar application of H_2O_2 up to a concentration of 48 μM increased the content of soluble solids (Figure 7B). The SS values obtained in fruits produced under different levels of salinity and foliar application of H_2O_2 in all treatments of the present study are above the standard (5 °Brix) [48], except in plants grown with ECns below 3.0 dS m^{-1} and without application of H_2O_2.

An effect similar to that of soluble solids (Figure 7B) was observed in the total sugar content (Figure 8), i.e., an increase with the increment in the electrical conductivity of the nutrient solution associated with foliar application of H_2O_2 up to the concentration of 48 μM. The increase in total sugar content observed mainly in plants grown under ECns of 4.2 dS m^{-1} and subjected to an H_2O_2 concentration of 48 μM may be a mechanism of acclimatization to salt stress caused by increased synthesis of metabolites [50].

5. Conclusions

An increase in the electrical conductivity of the nutrient solution from 2.1 dS m^{-1} negatively affects the production components of cherry tomatoes. However, it does not affect the post-harvest quality of the fruits. Despite the reductions observed in the production components, foliar application of hydrogen peroxide at concentrations esteemed between 22 and 25 μM attenuates the deleterious effects of salt stress on the number of fruits and ascorbic acid content and increases the total fruit production per plant of cherry tomato. On the other hand, foliar application of hydrogen peroxide at concentrations higher than 25 μM intensifies the effects of salt stress, causing reductions in the production of cherry tomatoes. The results obtained in the present study reinforce the hypothesis that foliar application of hydrogen peroxide at adequate concentrations attenuates the harmful effects of salt stress on the production components and post-harvest quality of cherry tomatoes. More studies are needed to understand how hydrogen peroxide acts on salt stress signaling via morphophysiological and biochemical analyses. In general, the use of hydrogen peroxide is a strategy of easy application and low cost for the farmer, which can enable the use of brackish water in the cultivation of cherry tomatoes, especially in arid and semi-arid regions, where the presence of these waters and the scarcity of fresh water for use in agriculture are common.

Author Contributions: Conceptualization, M.A.G. and G.S.d.L.; methodology, M.A.G., L.d.A.S. and V.K.N.O.; software, A.A.R.d.S., J.P.G. and R.T.d.F.; validation, M.A.G., G.S.d.L. and L.A.d.A.S.; formal analysis, A.A.R.d.S. and L.A.d.A.S.; investigation, M.A.G. and J.S.N.; resources, G.S.d.L. and R.G.N.; data collection, A.A.R.d.S.; writing—original draft preparation, M.A.G. and G.S.d.L.; writing—review and editing, A.A.R.d.S., G.S.d.L., C.A.V.d.A., S.S.d.S. and H.R.G.; supervision, H.R.G.; project administration, G.S.d.L. and L.A.d.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: CNPq (National Council for Scientific and Technological Development—Processo: 150927/2022-3), CAPES (Coordination for the Improvement of Higher Education Personnel) financial code—001, and UFCG (Universidade Federal de Campina Grande).

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the Graduate Program in Agricultural Engineering of the Federal University of Campina Grande, the National Council for Scientific and Technological Development (CNPq), and the Coordination for the Improvement of Higher Education Personnel (CAPES) for the support in carrying out this research.

Conflicts of Interest: The authors declare no conflict of interest.

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