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Effect of Electrical Conductivity Levels and Hydrogen Peroxide Priming on Nutrient Solution Uptake by Chives in a Hydroponic System

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Abstract: The use of water of high electrical conductivity has become common in hydroponic systems, especially in regions with water scarcity. However, the use of inferior-quality water can affect crop yields. In this scenario, some studies have tested the use of chemical conditioning agents such as hydrogen peroxide to minimize the negative effects of stress on plants. From this perspective, this study aimed to evaluate the action of priming with hydrogen peroxide as a salt stress attenuator on the nutrient solution uptake and productivity of chives in a hydroponic system. The study was conducted in a protected environment with a randomized block design with a split-plot arrangement. The treatments consisted of a main plot consisting of the electrical conductivity of the nutrient solution (1.0, 2.0, 3.0, 4.0, and 5.0 dSm^{-1}) and a subplot with five hydrogen peroxide concentrations (0.0, 0.15, 0.30, 0.45, and 0.60 mM). The increase in the electrical conductivity of the nutrient solution reduced bulb length, the solution volume applied, water uptake, total fresh mass, and the solution use efficiency by plants. Throughout the cultivation cycle in the hydroponic system, the consumption of nutrient solution was 459 mm lost by evapotranspiration. Acclimation with 0.60 mM hydrogen peroxide associated with 1 dSm^{-1} of electrical conductivity of the nutrient solution favors bulb diameter in chives. The increase in electrical conductivity compromises the productive yield of chives.

Keywords: *Allium schoenoprasum*; abiotic stress; soilless cultivation; use efficiency of the nutrient solution

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1. Introduction

Chive (*Allium schoenoprasum*) is a plant species of the family Alliaceae grown in tropical and temperate regions [1]. This vegetable has a high nutrient value and is rich in minerals, bioactive compounds, and substances with antioxidant and antihypertensive properties [2].

Chive cultivation is usually performed by family farmers in regions known as 'green belts,' which play significant economic and social roles and contribute to improving the income and quality of life of its producers [3]. In the last few years, hydroponic chive cultivation has been intensified in green belts in an effort to reduce water consumption and allow cultivation with water sources of high electrical conductivity [4–6].

Chives achieve maximum yields in plantations using water with electrical conductivities up to 0.7 dSm^{-1}, above which the yield is linearly reduced, and cultivation is compromised (both above and belowground) due to the high salt concentrations in regions where water shortage prevails [4,5]. Santos et al. [6] stated that, under hydroponic conditions, this electrical conductivity value could be increased, favoring cultivation with water of higher salinities. Salt stress limits the yield of vegetable crops by causing stomatal closure and thus reducing the transpiration rate, the internal CO_2 concentration, and the photosynthetic rates [7].

Recent studies have shown that using nutrient solutions with high electrical conductivity significantly reduces the percentage of total, shoot, and root dry matter; bulb diameter; bulb length; and the contents of chlorophyll ‘a’, ‘b’, and carotenoids, reflecting decisively on the nutritional performance, concentration of minerals, photochemical content, and secondary metabolites of chives [5,6,8–10]. Under hydroponic conditions with electrical conductivities ranging from 0.7 to 9 dSm^{-1}, there is an expressive reduction in all growth, physiological, biochemical, and production aspects in chive plants [4–6].

The accumulation of mineral salts in nutrient solutions provided to plants in hydroponic systems can cause oxidative stress and toxicity, triggering morphological, structural, enzymatic, and metabolic changes, and, in extreme cases, causing plant death. From this perspective, studying plant responses to water uptake under different electrical conductivities becomes essential [11].

In this scenario, aiming to mitigate the effects of stress caused to plants by the high electrical conductivity of nutrient solutions in hydroponic systems, seed acclimation (priming) with hydrogen peroxide (H_2O_2) has proved to be an efficient approach [6]. According to Qureshi et al. [12], the exogenous application of H_2O_2 triggers a cell signaling system in the plant metabolism of several species, stimulating the production of antioxidant enzymes, which, in turn, increase plants’ capacity to minimize the harmful effects caused by such stresses. Furthermore, Carvalho et al. [13] stated that, when applied to rice seeds, hydrogen peroxide mitigates the effects of salt stress by stimulating the accumulation of proteins and soluble carbohydrates, increasing water uptake.

Seed priming associated with alternative technologies for the utilization of saline and brackish water in plantations, e.g., hydroponics, which is notorious for the energy reorganization and absence of matric potential, clears the path, increasing plant production using low-quality water, which is often the only irrigation source in regions that withstand water shortage [14]. In addition, hydroponics has allowed producers to increase the plant tolerance threshold, constituting an alternative to reduce the effects of stress on crops.

The hypothesis to be elucidated is that priming with hydrogen peroxide in chive seedlings can attenuate salt stress due to the high electrical conductivities of the nutrient solutions in a hydroponic environment. The tolerance of chives to different electrical conductivities is influenced by salt concentrations in the nutrient solution, the time of exposure to salt, and phenological stages [4–6]. However, studies are scarce under hydroponic conditions, and there are fewer studies considering the effects of stress resulting from solutions with different water conductivities and the application of seed priming with H_2O_2 associated with hydroponic cultivation, aiming to quantify the crop’s water consumption.

From this perspective, this study aimed to evaluate the action of hydrogen peroxide priming as a salt stress attenuator on the nutrient solution uptake and the productivity of chives in hydroponic systems.

2. Materials and Methods

2.1. Location of the Experiment and Construction of the Hydroponic System

The study was conducted in a protected environment at the Agricultural Engineering Academic Unit of the Federal University of Campina Grande (UFCG), located in Campina Grande, PB, at the geographic coordinates 7°13′11″ S and 35°53′31″ W, and at an elevation of 550 m a.s.l. The experiment started on 25 May 2019 and ended on 28 August 2019.

During the experiment, some meteorological parameters inside the plant nursery were monitored using a digital thermohygrometer that recorded the maximum, mean, and minimum daily temperatures (°C) and the relative air humidity (%) throughout the cultivation cycle. For the cultivation cycle in the protected environment, the mean temperature and humidity values were 24 °C and 72%, respectively, and the maximum values were 30.5 °C and 81%, respectively, which are ideal temperature and moisture ranges for chive cultivation under protected conditions [6].

2.2. Establishment of the Hydroponic System

Five hydroponic benches were set up inside the plant nursery using 50 mm PVC tubes similar to nutrient film technique (NFT). The between-row spacing was 0.60 m, and the height of the tubes was 0.76 m, with a 2% slope so that the solution provided to each treatment could run across the profile through gravity. At the end of each profile, a structure was set up to direct the nutrient solution to the return piping into the reservoir, also through gravity, thus forming a closed circulation hydroponic system meant to save water and nutrients (Figure 1).

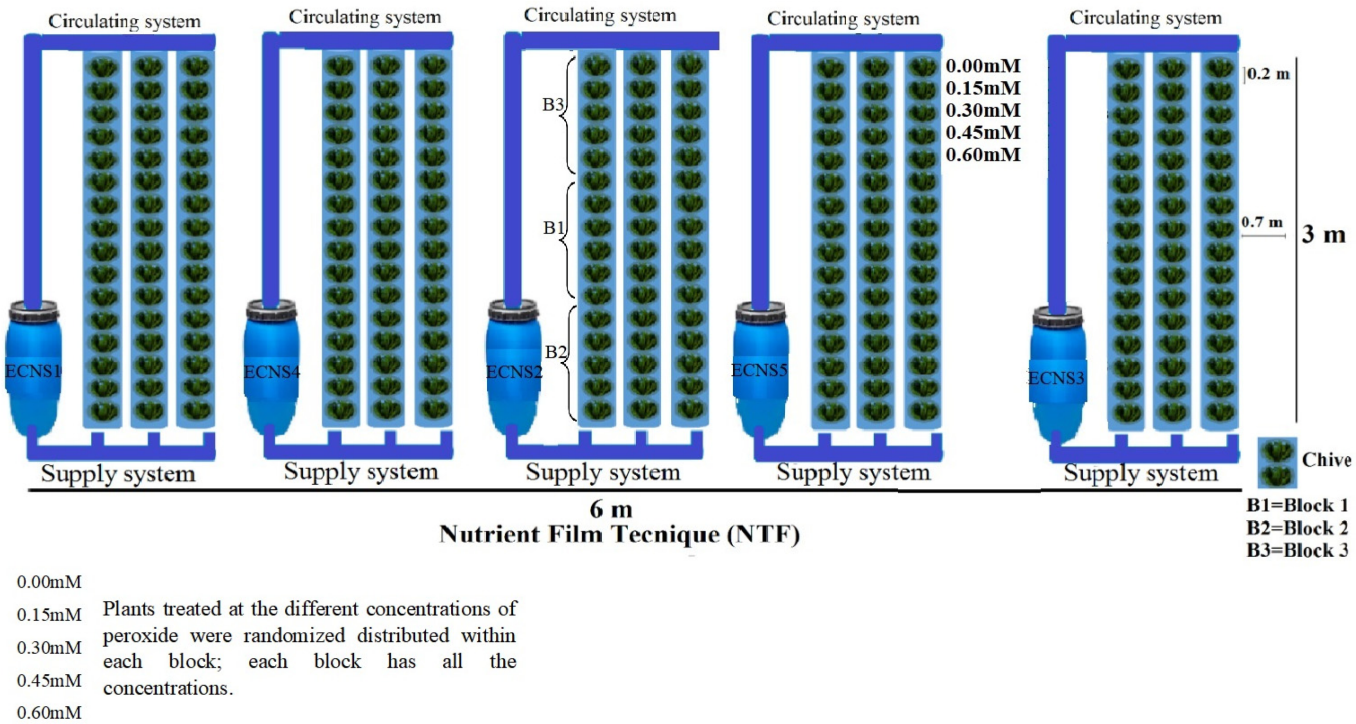


Figure 1. Experimental design of the NTF System, with the hydroponic growing benches.

The holes through which the plants were inserted were perforated using a driller coupled to a circular saw using a between-plant spacing of 0.20 m, with each profile having 3 m in length and receiving 15 plants. In the hydroponic system, the circulation of the solution in the profiles was scheduled to occur three times a day at 240 min intervals, following the recommendation of Silva Junior [5] for chives. Each profile had 15 chive plants at each different electrical conductivity (Solutions), totaling 48 plants at each profile and 225 plants in the experiment (Figure 1).

2.3. Treatments and Experimental Design

A randomized block design organized in a split-plot arrangement was adopted in the experiment so that the main plot was composed of five electrical conductivity levels of the nutrient solution (ECNS1 = 1.0, ECNS2 = 2.0, ECNS3 = 3.0, ECNS4 = 4.0, and ECNS5 = 5.0 dSm^{-1} at 25 °C). The subplot was composed of five hydrogen peroxide concentrations (0.0, 0.15, 0.30, 0.45, and 0.60 mM) used as stimulators of salt stress mitigation in chive seeds.

Plants treated at the different concentrations of peroxide were randomly distributed within each block, with three blocks in total, and with each block containing all concentrations. Each useful plot consisted of three plants spaced by 0.20 m within each hydroponic profile, distributed on five benches. In each experimental unit, two plants formed the edges, i.e., the first and the last plant. Each replicate consisted of three hydroponic profiles connected to a 100 L reservoir to store the nutrient solution, which was pumped by an electric pump.

The preparation of the nutrient solution followed the recommendations of Furlani et al. [15] for leafy vegetables. The formulation used to prepare the nutrient solution was the compound Hidrogood Fert® (Holambra, Brazil), which contains the following macronutrients: Nitrogen (N), Phosphorus (P), Potassium (K), Magnesium (Mg), Sulfur (S), and micronutrients: Boron (B), Copper (Cu), Molybdenum (Mo), Manganese (Mn), and Zinc (Zn). The concentration of each nutrient was as follows in all treatments: 75 g N; 67.5 g P; 210 g K; 27.75 g Mg; 32.25 g S; 0.45 g B; 0.075 g Cu; 0.52 g Mo; 0.37 g Mn; 0.15 g Zn. Calcium Iron Nitrate was added to the solution, also from Hidrogood Fert®. The recommendations indicated by Furlani et al. [15] for the preparation of the hydroponic solution for chives consisted of adding, for each 1000 L of water, 750 g of the Hidrogood Fert Compound, 550 g Calcium Nitrate, and 25 g Fe EDDHA. The water used to prepare the hydroponic solution was stored in a cistern belonging to the Federal University of Campina Grande—UFCG.

Sodium chloride was subsequently added to the solution to reach the desired electrical conductivity level, according to Richard's Equation (1) [16]. The nutrient solution was prepared using water stored in a cistern near the experimental area.

$$C = 640{*}ECns \tag{1}$$

where C—Salt concentration (sodium chloride) to be added to the nutrient solution, mgL^{-1}; ECns—Electrical conductivity to be achieved, dSm^{-1}.

In order to promote the mitigation (acclimation/priming) of the effect of different electrical conductivities of the nutrient solution, chive seeds were added in dark containers and soaked in different hydrogen peroxide concentrations for 24 h [17]. After the stress tolerance induction, sowing was performed in germination trays filled with a commercial substrate by sowing five seeds per cell, which were irrigated twice a day and kept in a plant nursery.

The chive cultivar 'Todo Ano Evergreen—Nebuka' was used in the study due to its adaptation to semi-arid conditions [6]. Fifteen days after sowing, the seedlings were transplanted into the hydroponic system. Then, the seeds were inserted in 180 mL plastic cups perforated at the sides and at the bottom and filled with a coconut fiber substrate, after which they were inserted into the holes of the hydroponic pipeline.

Throughout the cultivation cycle, the electrical conductivity and the pH were measured with conductivity and pH meters. The pH remained at 6.0 throughout the cultivation cycle.

The evapotranspiration inside the protected environment was determined by using a Class-A mini tank set up at the center of the plant nursery at 0.20 m from the ground, and the evaporation readings were performed daily using a ruler. The reference evapotranspiration (ET_0) was determined according to Equation (2), as previously described [18]. The alternative tank coefficient (Kp) of 1.0, recommended by Prados [19], was used in the experiment as the ideal parameter for mini tanks inside protected environments.

$$ET_0 = K_p{*}E_v \tag{2}$$

where ET_0—reference evapotranspiration, in mm day^{-1}; K_p—tank coefficient, non-dimensional; E_v—mini tank evaporation, in mm day^{-1}.

The volume of the nutrient solution to be applied in each profile was determined based on the reference evapotranspiration of the plant nursery added by 50%. Over time, as the uptake decreased, more solution was added to maintain the reservoir at 60% of its total capacity and thus prevent the lack of solution for the daily circulation schedule.

2.4. Variables Analyzed

Bulb length (BL) was evaluated 90 days after sowing using a ruler, whereas bulb diameter (BD) was measured at the base of the plant using a digital caliper (mm).

The contents of chlorophyll 'a', 'b,' and carotenoids were determined using five 0.6-cm^2 fresh leaf disks from the middle part of the plant, which were placed in Eppendorf tubes containing 1.5 mL of 80% acetone. The samples were then stored in a refrigerator for 48 h at 8 °C.

The extraction process was performed in triplicates. After this period, 0.5 mL aliquots were removed, and the absorbance of the solution was determined by spectrophotometry at 647, 663, and 470 nm. The total contents of chlorophyll a, b, and carotenoids were determined using the equations established by Lichtenthaler [20], and the results were expressed as µg g^{-1} of fresh matter (MF):

Chlorophyll 'a' = 12.25 (A663) − 2.79 (A647);

Chlorophyll 'b' = 21.50 (A647) − 5.10 (A663);

Total carotenoids = [1000 (A470) − 1.82 Chl 'a' − 85.02 Chl 'b']/198.

The total plant fresh matter (kg plant^{-1}), which represents the yield of chives, was measured using a precision balance.

The use efficiency of the nutrient solution was quantified based on the methodology of [20] using Equation (3).

$$EUS = \frac{MFT}{CSC} \tag{3}$$

EUS—use efficiency of the nutrient solution, kg plant^{-1} mm^{-1};

MFT—total fresh matter, kg;

CSC—consumption of the nutrient solution, mm.

The consumption of the nutrient solution per cycle was quantified by summing the volumes added throughout the cultivation cycle.

2.5. Statistical Analysis

The data obtained were checked for normality using the Shapiro–Wilk test and their homoscedasticity was determined by the Bartlett test at 5% of probability (Table 1).

After the basic assumptions of the ANOVA were met (Table 1), the analysis of variance was performed through the F-test. When significance was verified, regression was used to analyze the data.

The data that showed significant effects of the treatments were adjusted through linear and quadric polynomial regression (isolated factors and interaction between factors) and using the response surface model (for the interaction between factors). Tukey's test was applied when the regression model did not fit. The results of the interaction between factors are presented in the response surface format ($z = a + bx + cx^2 + dy + ey^2$) only for the equations with determination coefficients (R^2) higher than 0.60. For lower R^2 values, in the response surface model, the interactions were represented by linear and quadratic polynomial regression.

The statistical analyses employed the software programs Sisvar 5.6 [21] and Statistica 7 version 7.0 [22].

Table 1. Shapiro–Wilk normality test and Bartlett's test of homogeneous variances for the parameters of chives cultivated in a hydroponic system.

	Normality			Homoscedasticity		
Variable	**Test**	***p*-Value**	**Regular**	**Test**	***p*-Value**	**Homogeneous Variances**
VC (mm)	Shapiro–Wilk	0.21 *	Yes	Bartlett	0.9953 *	Yes
TFM (g)	Shapiro–Wilk	0.98 *	Yes	Bartlett	0.8287 *	Yes
TFM (kg)	Shapiro–Wilk	0.98 *	Yes	Bartlett	0.8287 *	Yes
ENS (kg plant^{-1} mm$^{-1)}$	Shapiro–Wilk	0.22 *	Yes	Bartlett	0.4211 *	Yes
BL (mm)	Shapiro–Wilk	0.15 *	Yes	Bartlett	0.2340 *	Yes
BD (mm)	Shapiro–Wilk	0.15 *	Yes	Bartlett	0.3080 *	Yes
CLOA (μg g^{-1} of (MF))	Shapiro–Wilk	0.10 *	Yes	Bartlett	0.8501 *	Yes
CLOB (μg g^{-1} of (MF))	Shapiro–Wilk	0.10 *	Yes	Bartlett	0.7058 *	Yes
CARO (μg g^{1} of (MF))	Shapiro–Wilk	0.10 *	Yes	Bartlett	0.8075 *	Yes

Volume of nutrient solution applied (VC); total shoot fresh matter marketed (MFT) and water-use efficiency of the nutrient solution (ENS); chlorophyll a (CLOA), chlorophyll b (CLOB), and carotenoids (CARO) * significant at the 5% probability level.

3. Results

3.1. Growth, Yield, and Solution Use Efficiency of Chives as a Function of Electrical Conductivity and Hydrogen Peroxide

The summary of the analysis of variance for the sources of variation referring to the electrical conductivity of the nutrient solution (ECNS), hydrogen peroxide concentrations (H_2O_2) (CP), and the interaction between them (ECNS × CP) on bulb length (BL, mm), bulb diameter (BD, mm), chlorophyll (CLOA, CLOB, and Carotenoids (CARO), μg g^{1} of MF), the volume of the nutrient solution applied (VC, mm), total shoot fresh matter marketed (MFT, kg), and water-use efficiency (ENS, kg plant^{-1} mm^{-1}) of chives 90 days after sowing are found in Table 2.

Table 2. Summary of the analysis of variance for bulb length, bulb diameter, chlorophyll 'a'(CLOA), 'b'(CLOB), carotenoids (CARO), volume of nutrient solution applied (VC, mm), total shoot fresh matter marketed (MFT, kg), and water-use efficiency of the nutrient solution (ENS, kg plant^{-1} mm^{-1}) in hydroponic chives 90 days after sowing.

Sources of Variation	**GL**	**F Statistics**							
		BL	**BD**	**CLOA**	**CLOB**	**CARO**	**VC**	**MFT**	**ENS**
Block	2	8.2 ^{ns}	3.9 ^{ns}	0.1 ^{ns}	0.6 ^{ns}	0.4 ^{ns}	1.4 ^{ns}	0.4 ^{ns}	0.5 ^{ns}
ECNS	4	34.9 **	8.1 **	1.2 ^{ns}	0.8 ^{ns}	1.8 ^{ns}	29.7 **	9.1 *	9.2 *
CP	4	2.5 ^{ns}	0.2 ^{ns}	0.4 ^{ns}	0.7 ^{ns}	0.05 ^{ns}	20.3 ^{ns}	1.0 ^{ns}	0.8 ^{ns}
ECNS x CP	16	1.5 ^{ns}	2.5 *	1.1 ^{ns}	0.8 ^{ns}	1.4 ^{ns}	3.3 ^{ns}	1.5 ^{ns}	1.6 ^{ns}
Residual 1	8	-	-	-	-	-	-	-	-
Residual 2	40	-	-	-	-	-	-	-	-
		mm		**μg g^{-1} of (MF)**			**mm**	**kg**	**(kg Plant^{-1} mm^{-1})**
General mean	-	10.2	6.1	848.5	349.4	166.0	3.0	0.03	0.01
CV1%	-	5.6	9.5	20.8	35.2	32.1	6.4	20.4	19.6
CV2%	-	8.3	8.5	14.7	28.7	24.8	8.0	18.4	18.1

** significant at 1%; * significant at 5%; ^{ns} non-significant.

The different electrical conductivities of the nutrient solution significantly influenced bulb length, bulb diameter, the nutrient solution volume applied, total fresh matter, and the water-use efficiency of the nutrient solution at the significance levels of 1% and 5%

(Table 2). Furthermore, the different hydrogen peroxide concentrations applied to the seeds for acclimation (priming), aiming to mitigate the effect of different electrical conductivities of the nutrient solution, did not influence any of the variables studied. However, there was a significant interaction between the electrical conductivity and the hydrogen peroxide concentrations at 5% of probability on bulb diameter 90 days after sowing para for the chive cultivar 'Todo Ano Evergreen—Nebuka' (Table 2).

The variables of chlorophyll 'a', chlorophyll 'b', and carotenoids were not influenced by the electrical conductivity of the nutrient solution or the hydrogen peroxide concentrations applied for seed priming (Table 2). The mean contents of CLOA, CLOB, and CARO were 848.5, 349.4, and 166.0 µg g^{-1} of MF, respectively, well below those reported by Silva et al. [8] for *Allium schoenoprasum* (23,820, 9840, and 6330 µg g^{-1}). When studying the isolated effect of hydrogen peroxide concentrations applied as priming on chive seeds when the plants were grown under hydroponic conditions, there was no significant difference between the different concentrations at the 5% probability level in bulb length, bulb diameter, chlorophyll "a", "b", carotenoids, volume of solution applied, total fruit mass, and nutrient solution use efficiency (Table 3).

Table 3. Mean values for BL, BD, CLOA, CLOB, CARO, VC, MFT, and ENS as a function of different hydrogen peroxide concentrations applied as priming to chive seedlings.

Concentrations (H_2O_2)	BL	BD	CLOA	CLOB	CARO	VC	MFT	ENS
	mm		µg g^{-1} of (MF)			mm	kg	(kg $Plant^{-1}$ mm^{-1})
0.00 mM	10.16 a	6.04 a	858.02 a	373.17 a	169.49 a	3.08 a	0.038 a	0.013 a
0.15 mM	10.58 a	6.17 a	894.94 a	341.21 a	164.58 a	3.08 a	0.040 a	0.013 a
0.30 mM	10.54 a	6.13 a	853.72 a	338.71 a	163.52 a	3.08 a	0.040 a	0.013 a
0.45 mM	9.74 a	6.11 a	761.24 a	323.36 a	167.65 a	3.08 a	0.038 a	0.012 a
0.60 mM	10.06 a	6.23 a	874.83 a	370.85 a	164.97 a	3.08 a	0.040 a	0.013 a

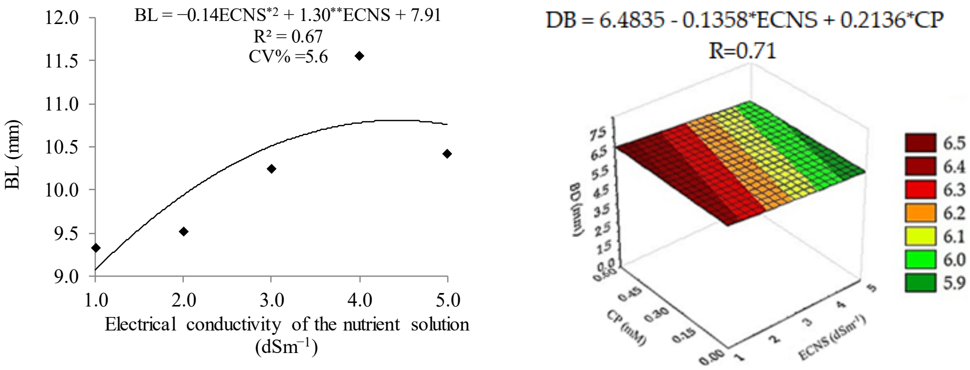
Means followed by the same lowercase letter in the column do not differ from each other by the Tukey's at 5% probability level.

The seed germination percentage of chives treated with hydrogen peroxide remained in accordance with the recommendation of the seed manufacturer, i.e., higher than 80%. It is noteworthy that, in the treatments with hydrogen peroxide application, there was faster germination and high uniformity, thus reaffirming the data of Santos et al. [23], who obtained 81% germination percentage for chives using the same cultivar and treatments used as in this study.

The mathematical model that best fit the bulb length parameter was the quadratic one, and the maximum yield for this variable was obtained at 4.64 dSm^{-1} of ECNS, corresponding to a BL of 10.9 mm (Figure 2a).

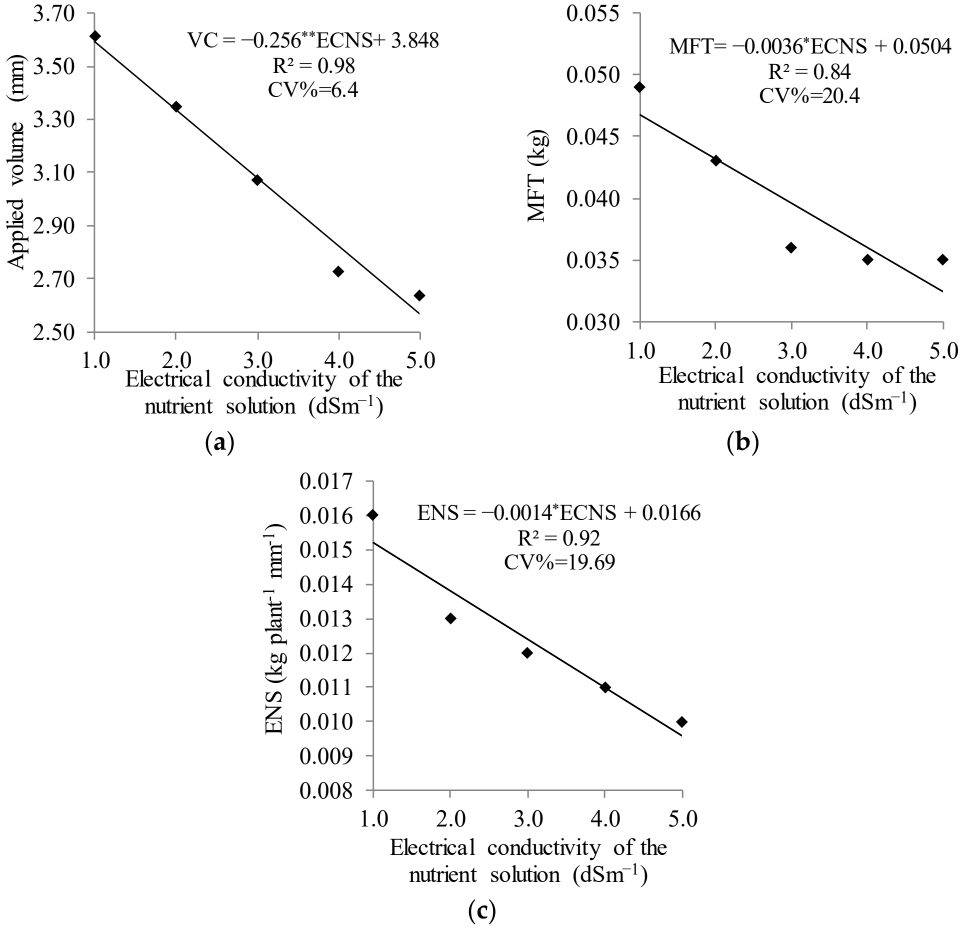
There was an interaction between ECNS × CP on bulb diameter, and the highest BD values (mm) were obtained at the lowest salinity of the nutrient solution (1 dSm^{-1}) associated with the highest hydrogen peroxide concentration applied during seed priming (0.60 mM) (Figure 2b). Furthermore, as the electrical conductivity of the nutrient solution increased, the stress-mitigating effect of hydrogen peroxide and bulb diameter decreased.

Mean values of the nutrient solution applied (a), total shoot mass marketed (b), and use efficiency of the nutrient solution (c) for chives 90 days after sowing in a hydroponic system for the isolated factor of the electrical conductivity of the nutrient solution are found in Figure 3.



(**a**) (**b**)

Figure 2. Bulb length (**a**) and bulb diameter (**b**) of chives subjected to different electrical conductivities of the nutrient solution and priming with hydrogen peroxide 90 days after sowing in hydroponic cultivation. ** significant at 1%; * significant at 5%.



(**c**)

Figure 3. Volume of the nutrient solution applied (**a**), total shoot mass marketed (**b**), and use efficiency of the nutrient solution (**c**) in a hydroponic system for the salinity levels of the nutrient solutions. ** significant at 1%; * significant at 5%.

When analyzing the volume of nutrient solution applied to chives 90 days after sowing in the hydroponic system, it was observed that as the electrical conductivity of the nutrient solution increased, the nutrient solution volume absorbed by plants decreased (Figure 3a), with the linear model best fitting the maximum volume obtained at the ECNS of 1 dSm^{-1} and the lowest at ECNS 5 dSm^{-1}, corresponding, respectively, to 3.592 and 2.568 m, with a decrease per unit increase of the electrical conductivity of the nutrient solution corresponding to 0.256 mm at each application cycle in the hydroponic system (Figure 3a). When comparing the ECNS of 1 dSm^{-1} with that of ECNS of 5 dSm^{-1}, a percentage reduction of 28.6% was observed in the volume of nutrient solution applied.

The mathematical model that best fit the total dry mass of chives as a function of the electrical conductivity of the nutrient solution was the linear model, i.e., as the electrical conductivity increased, the MFT decreased (Figure 3b), with every 1 dSm^{-1} increase in the electrical conductivity reducing the total fresh mass of chives by 3.6 g. This scenario indicates a 30.7% reduction when comparing the ECNS1 to the ECNS5.

The use efficiency of the nutrient solution in hydroponics under different electrical conductivity levels of chives highlighted a linear adjustment with a progressive reduction as the electrical conductivity of the nutrient solution increased, with the maximum use efficiency of the nutrient solution being obtained at 1 dSm^{-1}, corresponding to a EUS of 0.0152 kg per plant mm^{-1} of the solution provided to the system and a percent difference of 36.84%, between ECNS1 and ECNS5, i.e., the ECNS of 1 dSm^{-1} provides a use efficiency of 14.6 g mm^{-1} of nutrient solution applied (Figure 3c).

3.2. Water Consumption of Chives as a Function of Different Water Conductivities of the Nutrient Solution

Furthermore, when analyzing the mean uptake per plant and per cycle of chive plants as a function of the electrical conductivity of the nutrient solution (Table 4), there was a reduction in water consumption (in mm) per plant when the salinity of the nutrient solution increased, with the maximum uptake obtained at the electrical conductivity (ECNS) of 1 dSm^{-1}, i.e., the lower the ECNS, the more water is consumed by plants to perform the essential activities of their metabolism and, consequently, the higher their yield [7].

Table 4. Water consumption of chives cultivated in a hydroponic system, per plant and per cycle, as a function of different water conductivities of the nutrient solution.

Treatments	Mean Consumption (mm Plant)	Mean Consumption (mm Cycle)
ECNS1	6.38	459.0
ECNS2	5.92	426.5
ECNS3	5.43	391.0
ECNS4	4.83	347.6
ECNS5	4.66	335.4

4. Discussion

4.1. Growth, Yield, and Solution Use Efficiency of Chives as a Function of Electrical Conductivity and Hydrogen Peroxide

Depending on the electrical conductivity of water, stress causes damage to agriculture in all parts of the world, reducing plant growth and productivity. In this scenario, research seeking alternatives to mitigate the effects of salts on plants is essential, but it is a challenge to mitigate the implications of high electrical conductivity on plants under hydroponic cultivation. Therefore, the strategy of using priming with hydrogen peroxide in chive seeds to attenuate salt stress in hydroponic environments becomes an interesting alternative. The results indicate that the application of hydrogen peroxide (0.0, 0.15, 0.30, 0.45, and 0.60 Mm) did not attenuate salt stress due to the high levels of electrical conductivity (1, 2, 3, 4, and 5 dSm^{-1}) provided in the nutrient solution to chives in a hydroponic environment.

However, when 0.60 Mm of hydrogen peroxide was applied as priming, there were greater gains in bulb diameter in ECNS1. Furthermore, with the increase in electrical conductivity, the diameter was reduced, as well as the mitigating effect of H_2O_2. Therefore, it is possible that the concentrations of hydrogen peroxide applied to the seeds may have been insufficient to trigger the metabolism of chive plants in the cell signaling system, which stimulates the production of antioxidant enzymes that contribute to increasing the plant's ability to resist the harmful effects of salts.

Although no significant effects of the action of H_2O_2 on chive seeds have been verified as attenuating agents, these are initial studies that encourage further research with other hydrogen peroxide concentrations to obtain possible concentrations that may serve as attenuating agents. The hydrogen peroxide concentrations capable of acclimating seeds to abiotic stresses vary from 0.05 μM to 200 mM. This variation is related to the form of application, the time that the seed was exposed to hydrogen peroxide, and the morphological and physiological characteristics of each species [10,12,24].

Priming in chive seeds contributes to increasing seed performance by metabolically advancing seed germination, resulting in uniform seedling emergence, even though no statistical difference was found between the different concentrations regarding the growth, consumption, and production variables of chive plants grown in hydroponic systems. There were probably no significant differences between the hydrogen peroxide concentrations used as they were not enough to promote the accumulation of reactive oxygen species (ROS), which are substances produced in the mitochondria that coordinate the metabolism with the function of eliminating unnecessary cells, acting decisively in the plant's defense mechanism under salt stress conditions [6,12,25,26].

When hydrogen peroxide activates the molecules that contribute to accumulating ROS, the result is the mitigation of salt stress, contributing to osmotic adjustment and favoring development in terms of growth, photosynthesis, and plant reproductive organs, helping increase the tolerance of plants to stress, i.e., hydrogen peroxide acts as an attenuator [6,10,26].

When exposed to salt stress due to high electrical conductivities of the nutrient solution even under hydroponic cultivation, chive plants showed reduced bulb diameter, water use efficiency, and nutrient solution consumption as the ECNS was increased by 1 dSm^{-1}, with a mean percent reduction of 30.76%. Our results reveal that a high electrical conductivity of the nutrient solution causes toxicity in hydroponic chives and failure in the plant's osmotic adjustment, even after priming. A relevant factor is that chlorophyll synthesis was not altered when plants underwent salt stress, indicating that the osmotic adjustment of chives occurs mainly as a function of increased chlorophyll synthesis.

High salt concentrations in the nutrient solution could negatively influence the essential metabolic processes for plant development, including nutrient uptake [27]. In this scenario, the nutrient uptake, transport, and assimilation processes of the nutrient solution do not occur adequately due to the antagonistic and competitive effects of salt excess and the pH increase in the nutrient medium, resulting in nutrient imbalances and reduced plant growth and development [28,29]. It should be noted that hydroponic cultivation tends to reduce the impacts of high electrical conductivities by adding nutrients into the medium, reducing such impacts by the absence of matric potential [8].

The lower carotenoid content in relation to the chlorophyll values is related to the inverse relationship between these variables, with higher chlorophyll contents possibly justifying the lower carotenoid values in chives. These variations in the contents of chlorophyll and total carotenoids can be influenced by the climatic conditions to which the plants were subjected [7,8].

It is evident that the synthesis of chlorophyll and carotenoids is essential to quantify the final quality of green vegetables since their chlorophyll forms are sensitive to heat, oxygen, light, enzymes, the action of metals, and oxidation, with the latter being the leading cause of carotenoid degradation, depending on oxygen availability, the type of carotenoids, and their physical state. As a result, this degradation is continuously stimulated by light, heat, metals, oxidative enzymes, and peroxides and is inhibited by antioxidants [8].

The electrical conductivity of the nutrient solution negatively influenced the bulb length of chives, although below the threshold found by [4] under direct cultivation. This result is justified by the fact that hydroponic cultivation contributes to reducing the effects of salts on plants compared to direct cultivation due to the absence of matric potential and the saturation state of plants, increasing the free energy of water and facilitating its uptake by plants [5].

The reductions in bulb diameter as a function of the electrical conductivity of the nutrient solution could be related to stomatal closure and reductions in gas exchange due to the stress condition, thus reducing the uptake of the nutrient solution and limiting plant growth [30].

The electrical conductivity of the nutrient solution [31] above the plant tolerance threshold is reflected in the reduction in crop growth and development even under hydroponic conditions, which may have contributed to the reduced bulb diameter of chives. Recent studies using hydrogen peroxide to mitigate the effect of salt stress corroborate that this attenuator can influence physiological responses to stress, such as stomatal opening and closing [6,11]. The beneficial effects of hydrogen peroxide on stress effects could be associated with its role as a signaling molecule, regulating several metabolic pathways [12,32]. It has been reported that the increase in the electrical conductivity of the nutrient solution decreases water and nutrient uptake; as a result, a lower water volume needs to be applied in the circulation system at higher electrical conductivity levels of the nutrient solution. These results are similar to those obtained by Cruz et al. [33] when studying the stress index, water potential, and leaf succulence of cauliflower cultivated in a hydroponic system of high electrical conductivity.

Our results reveal linear reductions in the nutrient solution application rate observed in all electrical conductivity regimes. The total consumption of the nutrient solution was not changed between treatments, or only partially since water uptake by plants was cumulatively reduced, corroborating the research findings on the effect of NaCl or macronutrient-imposed salinity on the crop yield and water use efficiency of hydroponic basil [34].

The fresh mass reduction in plants cultivated in hydroponic systems with high electrical conductivity of the nutrient solution is a classic plant response observed by different authors in several vegetable crops [6,8,27,34,35]. This result is attributed to a reduction in the water potential of the external solution generated due to the osmotic effect of the salt present in the nutrient solution, hindering water and nutrient uptake by plant roots, which reduces leaf turgor and the MFT [36].

The ENS reduction is justified by the negative effect caused by salts present in the nutrient solution on the total fresh matter of chives plants. It should be noted that the use efficiency of the nutrient solution is important when working with nutrient solutions with high electrical conductivity since salt stress can cause higher uptake reductions compared to plant production.

Under water or salt stress, the water use efficiency can vary due to the reduction in stomatal conductance, which affects the photosynthetic rate more intensely than leaf transpiration rate [7]. When this process becomes severe, cell dehydration in the mesophyll inhibits photosynthesis, thus affecting the mesophyll metabolism, water use efficiency, and crop yield.

There was a reduction in the use efficiency of the nutrient solution of more than 20% when the plants were subjected to different electrical conductivities of the nutrient solution. This result may be more apparent when the species is susceptible to salt stress. Our results are similar to those obtained by Faliagka et al. [34] and Evanidi et al. [37] when studying basil subjected to different electrical conductivities of the nutrient solution, observing a 25% reduction in the use efficiency of the nutrient solution.

4.2. Water Consumption of Chives as a Function of Different Water Conductivities of the Nutrient Solution

The maximum consumption of nutrient solution (<460 mm cycle) was obtained at an electrical conductivity of 1 dSm^{-1}. From this value on, there was a reduction in consumption. This value is considered acceptable for hydroponic chive cultivation since the water consumption of this crop under field conditions is superior to 550 mm per cycle [3]. Quantifying water consumption during the cultivation cycle in hydroponic systems can contribute to improving and planning water resources in any region by estimating the water volume to be used before the crop is established in the hydroponic system [38]. This parameter is an efficient guideline for designing hydroponic systems, aiming to collect and store water for this purpose in green belts.

The water uptake reductions recorded for hydroponic chive cultivation when the seeds were subjected to acclimation with hydrogen peroxide and different electrical conductivities of the nutrient solution are within the acceptable range, as reported by Paulus [39] in their study with hydroponic lettuce, obtaining acceptable NFT reductions from 3.9 to 10.0% per unit increase in the electrical conductivity of the nutrient solution in two cultivation cycles.

When studying cumulative water consumption in hydroponic coriander using brackish water, [9] observed reductions of 5.26 and 5.85% per unit increment in the ECw for the periods of 1–20 and 1–24 DAT, respectively. Our results reveal similar conclusions with different species, indicating that the higher the electrical conductivity of the nutrient solution in hydroponic systems, the lower the total nutrient uptake by plants due to the reduction in the osmotic potential of the nutrient solution, delaying the transport of water from roots to fruits and leaves, with negative effects on expansion, growth, and production [40].

The use efficiency of the nutrient solution of 14.6 g for each mm of nutrient solution lost by evapotranspiration is considered acceptable. This result corroborates the data of Mendez-Cifuentes et al. [41] in a study on different open and closed hydroponic systems, who observed that in order to produce 1 kg of vegetables in an open cultivation system, approximately 53 L of water is required to achieve a yield of 95%, with 86% water consumption. On the other hand, in the closed system, the nutrient solution volume required is only 22 L.

Even under hydroponic conditions in which water and nutrients are supplied in a form that is readily assimilable by the plants, the different electrical conductivities of the nutrient solution tend to reduce water and nutrient uptake and productivity [8,26,40]. This result may be less evident when the species is less susceptible to salt stress and when subjected to acclimation with hydrogen peroxide [6,8].

5. Conclusions

The increase in electrical conductivity of the nutrient solution reduces bulb length, volume applied, water consumption in the solution, total marketable fresh mass, and the use efficiency of the nutrient solution by plants. Acclimation with hydrogen peroxide alone did not influence the yield of chives in a hydroponic system. The contents of chlorophyll a, b, and carotenoids are not influenced by the electrical conductivity of the nutrient solution or the hydrogen peroxide concentrations used for the acclimation. The highest consumption of nutrient solution by chive plants throughout the cultivation cycle was 459 mm, lost by evapotranspiration. The acclimation of chive seeds (0.60 mM) associated with 1 dSm^{-1} solution is the best combination for bulb diameter. Each increase of 1 dSm^{-1} in the electrical conductivity of the nutrient solution reduces the total fresh mass of chive plants by 1.4 g. The electrical conductivity of the nutrient solution to obtain the maximum yield of chives in hydroponic cultivation is 1 dSm^{-1}.

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