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Article

Influence of Colored Shade Nets and Salinity on the Development of Roselle Plants

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Abstract: Adequate fertilizer concentration and use of shade nets can favor the development and yield of agricultural crops. The objective of this investigation was to evaluate the growth of roselle plants with nutrient solutions of different electrical conductivities (EC_{ns}) (1.0, 2.0, 3.0, 4.0 and 5.0 dS m^{-1}) and under different colored shade nets (red, blue, black) compared with full sun. The experiments were conducted in a controlled greenhouse environment and in full sun in the Plant Production Department of ESALQ-USP, Piracicaba, SP, Brazil. The experiments were organized using a 4 × 5 randomized block design. The results of analysis of variance and regression showed a significant impact of EC and colored shade nets on plant height, stem diameter, number of leaves, number of flowers, fresh and dry mass of shoots and fresh and dry calyxes. The data were subjected to analysis of variance and regression, which showed a quadratic effect for the variables studied, with increasing values up to 3.0 dS m^{-1}; after this value, there was a decrease. Increasing EC_{ns} up to approximately 3.0 dS m^{-1} promoted increments of 2.34% in plant height, 7.21% in number of leaves, 19.76% in shoot fresh mass and 12.38% in shoot dry mass.

Keywords: *Hibiscus sabdariffa* L.; medicinal plants; nutrient solution; solar radiation

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1. Introduction

Roselle (*Hibiscus sabdariffa* L.) is a subtropical plant in the Malvaceae family, widely cultivated in Africa and Asia and in countries with a tropical climate [1]. Among the various genotypes and varieties, var. sabdariffa is an annual herbaceous plant that can grow up to 3 m in height. It has a deep root, an erect stem, ovate to lanceolate leaves with three to seven lobes and serrated margins. The leaves are dark green and may have reddish pigments. The flowers can be light yellow to pink, red, orange or purplish-red with a reddish center at the base of the staminal column. The calyx is dark red, with a diameter of 2.5–3.5 cm and a length of 4.2–7.2 cm [2].

This species has been widely studied and used in the pharmaceutical industry because its calyxes are rich in anthocyanins, flavonoids, triterpenoids, phenolics and alkaloids [3]. These antioxidants are important because they act as angiotensin enzyme conversion inhibitors and can be used in the treatment of hypertension [4]. They can also regulate the digestive enzymes α-glucosidase and α-amylase. It has been recommended to investigate fertilization programs for achieving a sustainable production system of such crops [5]. Considering the importance of roselle in food and medicinal formulations, more research needs to be carried out where it is grown to optimize fertilizer use and determine the influence of salt stress and light on the development of *Hibiscus sabdariffa* plants.

Among the factors that influence the production, quality and yield of this medicinal plant, environmental factors such as drought, high temperature, high light incidence and salinity affect the growth of roselle plants and lead to significant losses in yield [6]. For a plant species to maintain a good growth rate, it needs optimal light intensity to perform photosynthesis and other biological activities [6].

Soil salinity can occur either naturally or anthropogenically and is characterized by the accumulation of soluble salts in the soil. The natural salinization processes include the transport of sediments to non-salinized areas, the rise of salts by capillarity to the soil surface and high evapotranspiration rates [7,8]. The anthropogenic actions that most contribute to the process of soil salinization are the use of water with a high salt content for irrigation [8], the practice of irrigation without a drainage system in susceptible areas and the application of fertilizers and pesticides with a high saline index [7,9].

Soil salinity is determined by measuring the electrical conductivity (EC) of a soil suspension. The EC corresponds to a measure of the ease of passage of an electric current in a solution in which ionic solutes are present and constitutes an indirect estimate of the content of dissolved salts in a suspension of the substrate in which the plants are grown. In general, the greater the amount of chemical fertilizer applied to the substrate, the higher the EC value [10]. Salt stress can cause photochemical, physiological, metabolic, morphological and molecular damage, limiting plant growth and development and reducing the yield of agricultural crops [11–13]. The metabolic disturbances caused by salinity can lead to major changes in the metabolism of organic solutes essential for cell function. Changes in the levels of organic solutes, such as amino acids (especially proline) and proteins, can reflect metabolic changes associated with resistance and/or sensitivity to salinity [13].

In view of the effects caused by excess light and salts in the soil, it is important to conduct studies focused on the influence of abiotic factors on the production of roselle to mitigate the effects of salt and light stress. Shade nets can be used to disperse solar radiation, providing better light distribution in the greenhouse and uniformity of temperature and relative humidity that favor uniformity in plant growth [14].

Other factors that influence the growth and productivity of agricultural crops include temperature, water availability and solar radiation, which can alter the physiological and anatomical processes of plant species [15]. Since plants under low irradiance predominantly have shorter, thinner leaves with a low chlorophyll/nitrogen ratio and a lower density of stomata [16,17], it is usually necessary to cool the greenhouse during the hottest periods of the year. Methods for accomplishing this include shading with plastic or thermal screens to attenuate the effect of solar radiation during cultivation. In addition, this technique allows for the manipulation of micrometeorological variables to adjust environmental conditions for optimal crop growth and increased productivity [18].

The use of colored shading meshes can selectively alter the intensity of certain wavelengths in the visible range, reducing absorption and causing different physiological effects in cultivated plants [19,20].

In a study carried out the development of a crop of lisianthus (*Eustoma grandiflorum*) in the municipality of Piracicaba, São Paulo [21], the plants were grown in a protected environment under different light transmission meshes colored blue, black and red. According to the study, it was found that cultivation under the red mesh resulted in greater stem height compared to the blue mesh on all the analyzed dates, with a final difference between the two treatments of 12.6 cm.

Therefore, the objective of this study was to evaluate the growth of roselle plants with different levels of electrical conductivity of the nutrient solution and under different colored shade nets.

2. Material and Methods

2.1. Experimental Location and Climatic Data

Parallel experiments were conducted in a greenhouse and in the open air, both located in an experimental area specifically reserved for the cultivation of ornamental plants linked to the Plant Production Department (Figure 1) at the "Luiz de Queiroz" College of Agriculture, University of São Paulo (ESALQ/USP), in the municipality of Piracicaba, SP, Brazil (22°42′ South latitude and 47°38′ West longitude, and altitude of 546 m). The climate of the region is classified as Cwa, subtropical climate, with hot summers and dry winters [22].

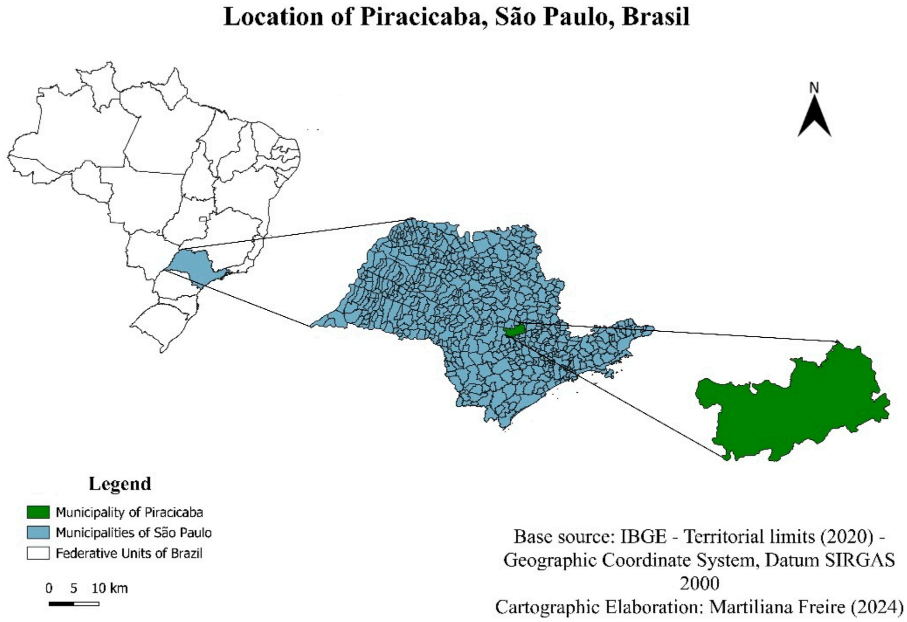


Figure 1. Location of the experimental area at ESALQ/USP, Piracicaba-SP, Brazil.

The experimental units were in a greenhouse with a single span, 6.4 m in width and 36 m in length, covered by a light-diffusing polyethylene cover with 100% transmissivity and different light transmission nets (ChromatiNET®, Ginegar, Leme, São Paulo, Brazil) of 5 mm thickness and 50% shading level. The tunnel was oriented in a north/south direction and was subdivided into three equal parts for treatment with the different shade nets. The west side was covered with a net of the same color as the corresponding treatment to avoid overlapping or interference in the first hours of the day. The open-air plots were situated in an area in the field next to the greenhouse.

Roselle plants, both inside and outside the greenhouse, were cultivated in a commercial substrate, Biogrow Fibra/Composto Standard (AgroLink® Substratos, Artur Nogueira, São Paulo, Brazil) consisting mainly of composted pine needles, composted pine bark, sphagnum peat and coconut fiber.

Chemical characterization of the substrates (Table 1) was performed by chromatography on a cation exchange resin to determine exchangeable phosphorus (P), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) contents, expressed in mg dm^{-3}, and potential acidity (H + Al), quantified by flame emission photometry [23]. These data were then used to calculate the cation exchange capacity (CEC at pH 7.00), sum of bases (SB) and base saturation (V). Concentrations of soluble ions, pH and electrical conductivity (EC) were determined by previously published methods [24].

Micrometeorological variables within the protected environment were monitored by an automatic station with a data acquisition system consisting of a CR1000 Datalogger (Campbell Scientific®, Linden, NJ, USA) with an HMP45C thermohygrometer sensor (Vaisala®, Vantaa, Finland) for collecting temperature and relative humidity readings, a CS-100 barometric pressure sensor and an LI200X silicon-photodiode pyranometer sensor (LI-COR®, Campbell Scientific, Lincoln, NE, USA) to measure global solar radiation. Throughout the experimental period, the minimum temperature was 3.10 °C, and the maximum temperature was 36.54 °C, with an average of 27.21 °C. The minimum relative humidity was 18.62%, the maximum RH was 91.10 %, and the average RH was 45.66%. The average value for solar radiation recorded during the experimental period was 12.51 MJ m^{-2} day^{-1} (Figure 2).

Table 1. Chemical and hydraulic characterization of the substrate.

pH (0.01 M $CaCl_2$)	5.3
Density (Organic residue)	0.33 g cm^{-3}
Total Organic Matter (Combustion)	412.0 g dm^{-3}
Phosphorus (P_2O_5)	45 mg dm^{-3}
Potassium (K_2O)	15.6 mg dm^{-3}
Calcium (Ca)	108 mg dm^{-3}
Magnesium (Mg)	36.0 $mmol_c$ dm^{-3}
Boron (B)	0.76 mg dm^{-3}
Copper (Cu)	0.7 mg dm^{-3}
Iron (Fe)	89 mg dm^{-3}
Manganese (Mn)	13.2 mg dm^{-3}
Zinc (Zn)	3.7 mg dm^{-3}
Cation Exchange Capacity (CEC)	212.0 $mmol_c$ dm^{-3}
$H+Al^{+3}$	52 $mmol_c$ dm^{-3}
V	75%
SB	160 $mmol_c$ dm^{-3}
Water Retention Capacity (WRC)	92.79%
Electrical conductivity (EC)	1.0 dS m^{-1}

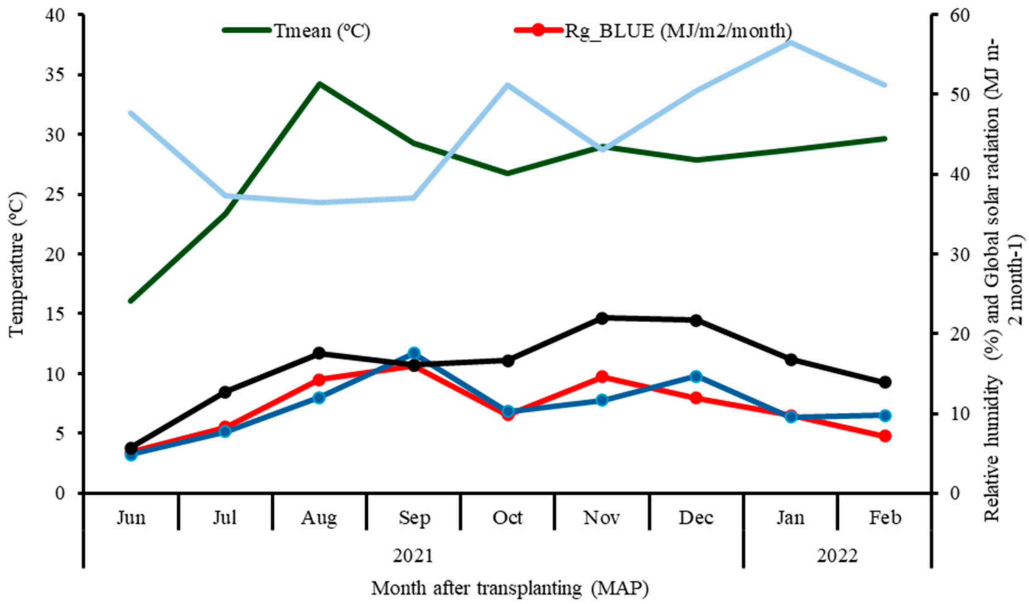


Figure 2. Daily mean air temperature (°C)—represented by green, daily mean relative humidity (%)—represented by blue and global solar radiation (MJ m^{-2} $month^{-1}$) inside the controlled environment during the experimental period—represented by the colors corresponding to each mesh: red, blue and black.

Data from the ESALQ weather station, located approximately 300 m away, were used for monitoring outside the greenhouse. Throughout the cycle, the minimum temperature was 8.89 °C, the maximum was 39.36 °C, and the average was 28.17 °C. The minimum relative humidity (RH) was 20.12%, the maximum was 90.61%, and the average RH was 68.77%. The average value for solar radiation recorded during the experimental period was 18.36 MJ m^{-2} day^{-1} (Figure 3).

Prior to the daily collection of global solar radiation values, the LI200X silicon-photodiode pyranometer (LI-COR®, CAMPBELL SCIENTIFIC, INC., Logan, UT, USA) sensors were calibrated with a commercial Eppley pyranometer, whose sensor served as the standard (Figure S1). Measurements were carried out over a period of 20 days at 15 min intervals under clear sky atmospheric conditions. The trend of global solar radiation obtained with the calibrated pyranometers had good linearity, with coefficients of determination of

0.99 and 0.98 (Figure S2). Therefore, the previous calibration showed that the sensors were suitable for the solar radiation measurements performed.

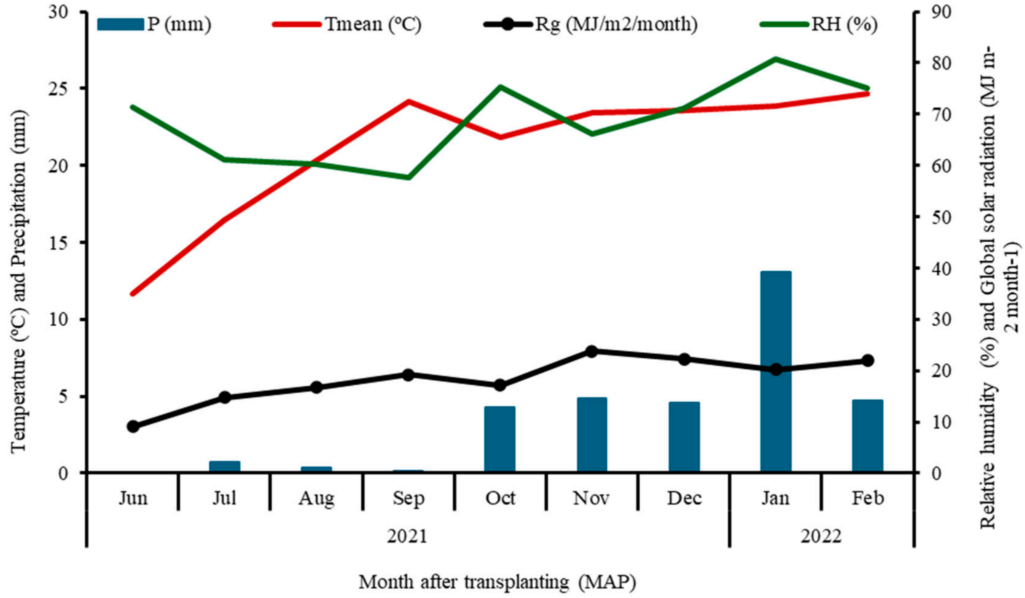


Figure 3. Rainfall (mm)—represented by the blue column, daily mean air temperature (°C)—represented by red, mean relative humidity (%), represented by green and global solar radiation (MJ m^{-2} $month^{-1}$) in the open air during the experimental period—represented by black.

2.2. Experimental Design and Applied Treatments

A drip irrigation system was used. The main line, sub-main lines and accessories were made of polyvinyl chloride (PVC). The lateral lines were made of polyethylene and equipped with pressure-compensating drippers with a flow rate of 2.0 L h^{-1}, which were connected to microtubes with drip sticks at the outlet of each experimental unit.

The reservoirs used for storing the nutrient solutions for the treatments were separate 200 L drums (Figure S3). Valves were installed at the outlet of the reservoirs and at the beginning of each lateral line to allow for independent irrigation for each treatment. A drum with only water was also included in the setup to wash the pipes before starting irrigation with each salinity level to prevent contamination between the solutions. The irrigation system was evaluated for Christiansen's uniformity coefficient (CUC), whose value was 92% [25].

Fertigation was performed every two days to raise the moisture content of the substrate to 100% of its water storage capacity, and the volume of water applied was determined by gravimetry using a digital industrial scale (Marte Científica®, São Paulo, São Paulo, Brazil) with a capacity of 60 kg and accuracy of 5 g. The mass of the pot + substrate + plant set was determined as the average mass of four pots per treatment. The treatments consisted of five levels of EC of the nutrient solution (1.0, 2.0, 3.0, 4.0 and 5.0 dS m^{-1}), managed by fertigation for the 10 months of cultivation of the roselle crop (*Hibiscus sabdariffa* L.), var. sabdariffa, and four colors of shading net (red, blue and black) in the greenhouse compared with no shading in full sun in the field. The seedlings were grown between April and May 2021 and transplanted in June 2021, and the plants were harvested in February 2022.

The macronutrients used were prepared according to the Hoagland nutrient solution [26] (Table 2), based on an electrical conductivity (EC) of 2.0 dS m^{-1}. EC levels below the reference were obtained by diluting the nutrient solution, whereas EC levels above the reference were obtained by concentrating the solutions to obtain the levels necessary for the experiment.

Table 2. Nutrient concentrations (mg L^{-1}) of the nutrient solutions estimated for each treatment. EC = electrical conductivity.

EC (dS m^{-1})	N	P	K	Ca	Mg	S	Cl
1.0	78.10	11.51	87.21	74.52	18.07	23.84	-
2.0	156.21	23.03	174.42	149.05	36.14	47.68	-
3.0	234.31	34.54	261.62	223.57	54.21	71.52	-
4.0	312.42	46.06	348.83	298.09	72.28	95.36	-
5.0	390.52	57.57	436.04	372.62	90.35	119.20	-

The plots were arranged in a protected environment and in the field in a factorial design 4 × 5 according to a randomized block design, with five levels of EC, four types of cover and four replicates, totaling 80 experimental units (Figure S4). Each plot consisted of pots containing one plant each, spaced 0.50 m × 0.30 m apart, which resulted in a population of 20 plants per block.

Sowing was carried out in trays with 128 cells containing a commercial substrate, whose average nutrient composition was (g kg^{-1}) 632.0 OM, 6.0 N, 7.7 P_2O_5, 3.6 K_2O, 2.44 Ca, 20 Mg, 11.4 S and 11.0 Fe; and micronutrients (mg dm^{-3}) 176 Mn, 35 Cu, 135 Zn, 340 B and 15 Mo. After emergence, the seedlings were fertigated daily using a nutrient solution with electrical conductivity (EC_{ns}) maintained at 0.5 dS m^{-1}. Roselle seedlings were transplanted to 15 dm^3 polyethylene pots 42 days after sowing when they had three true leaves.

2.3. Measurements

The heights of all plants in the plots were measured with a 10 m tape measure from the level of the substrate to the inflection of the highest leaf. The measurements were taken at 30-day intervals, from 30 to 300 days after transplanting, and the means were calculated for each treatment. The number of leaves per plant was counted at 30-day intervals, starting from 30 days after transplanting. The number of flowers was counted on a weekly basis, starting from 90 days after transplanting.

Stem diameter was determined with a digital caliper at 30-day intervals, starting from 30 days after transplanting. Shoot fresh mass, shoot dry mass, calyx fresh mass and calyx dry mass were determined using an analytical scale (0.01 g precision). After determining shoot fresh mass, the plant material was packed in paper bags and dried in a forced-air oven at 65 °C (±1) until a constant mass was reached.

2.4. Statistical Analysis

The evaluated parameters were subjected to analysis of variance by the F test at 0.05 and 0.01 probability levels, followed by decomposition whenever the interaction was significant. Once the significance of the data was checked, the means of growth traits were compared using the Tukey test at $p < 0.05$. The relationship between EC and growth trait for each parameter was subjected to regression analysis.

3. Results

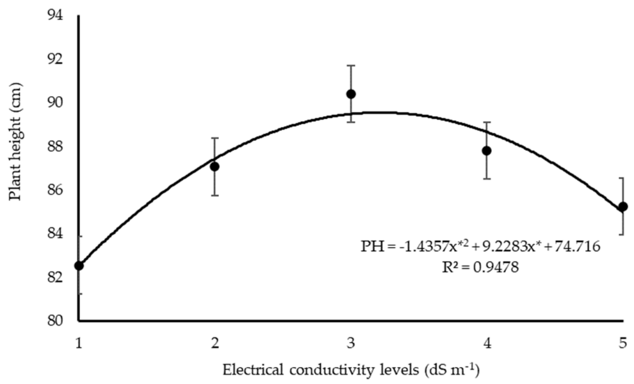
The colored shading nets caused significant differences ($p < 0.01$) in plant height, stem diameter, number of leaves, number of flowers, shoot fresh mass, shoot dry mass, calyx fresh mass and calyx dry mass. The electrical conductivity of the nutrient solution (EC_{ns}) also influenced ($p < 0.01$ to $p < 0.05$) plant height, stem diameter, number of leaves and number of flowers; EC_{ns} also influenced ($p < 0.01$) shoot fresh mass and shoot dry mass. The effect of the shading nets was also significant ($p < 0.05$) on EC_{ns} (SN × EC_{ns}), number of leaves and number of flowers (Table 3).

Table 3. Summary of the analysis of variance for plant height (PH), stem diameter (SD), number of leaves (NL), shoot fresh mass (SFM), shoot dry mass (SDM), calyx fresh mass (CFM), calyx dry mass (CDM) and number of flowers (NF) of roselle plants under different shade nets and levels of EC of the fertigation solution (EC_{ns}).

Source of Variation	Mean Square								
	DF	PH	SD	NL	SFM	SDM	CFM	CDM	NF
Colored shade net (SN)	3	1162.47 **	56.20 **	9987.75 **	32,656.27 **	19,987.75 **	19,620.11 **	442.87 **	7611.88 **
Quadratic Regression	1	461.78 **	23.82 **	12,901.79 **	67,276.45 **	7548.24 **	20.04 ^{ns}	7.58 ^{ns}	672.07 **
Elect. conductivity (EC_{ns})	4	137.73 *	12.96 **	5008.77 **	152,448.56 **	3248.82 **	600.84 ^{ns}	7.31 ^{ns}	47.99 **
SN × EC_{ns}	12	18.78 ^{ns}	1.00 ^{ns}	631.05 *	6038.74 ^{ns}	340.52 ^{ns}	1002.81 ^{ns}	23.62 ^{ns}	24.59 **
Residual	57	54.13	0.57	307.62	4880.43	383.35	18.13	2.042	2.33
CV (%)		8.49	7.56	17.12	17.47	21.09	21.09	26.70	7.83

**—significant at $p < 0.01$, *—significant at $p < 0.05$, ^{ns}—non-significant by the F test at $p < 0.05$. DF: degrees of freedom; SN: colored shade net; EC_{ns}: electrical conductivity of the fertigation solution; CV (%): coefficient of variation. Residual analysis was performed for all significant regressions with results at normal limits in the range (3; −3).

The greatest value for plant height (PH) (89.55 cm) was obtained with an EC_{ns} of 3.21 dS m^{-1}. For EC_{ns} levels of 1.0 and 5.0 dS m^{-1}, reductions of 5.63 and 2.82%, respectively, were observed. For an EC_{ns} of 3.0 dS m^{-1}, plant height was equal to 102.34 cm, with an increase of 2.34% (Figure 4A), and at an EC_{ns} of 4.0 dS m^{-1}, the value was 101.40 cm, with an increase of 1.40% compared to the EC of the standard nutrient solution [27].



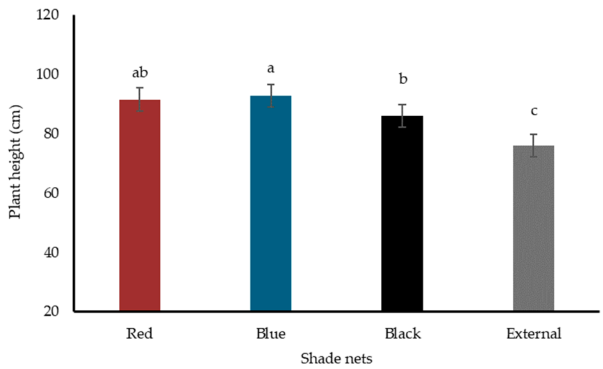
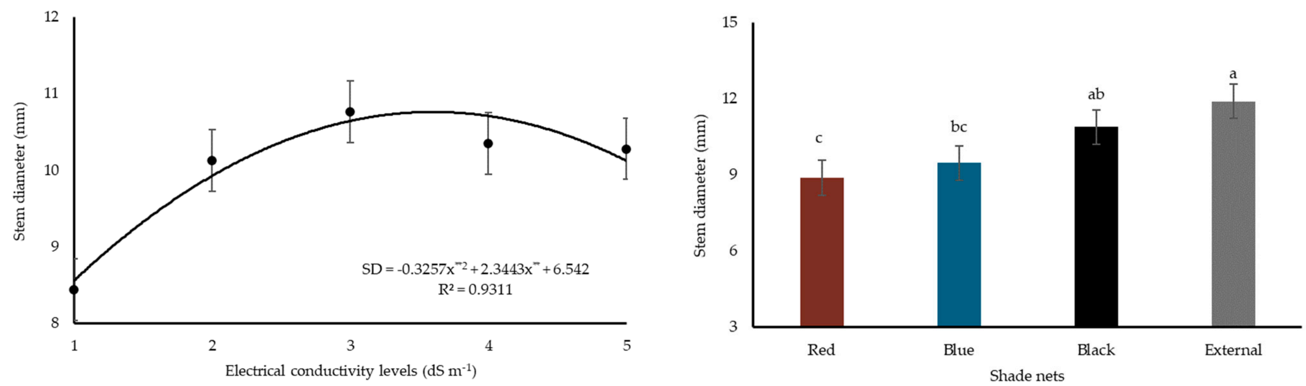


Figure 4. Plant height (PH) of roselle plants with different electrical conductivity of the nutrient solution (**A**) and under different shade nets (**B**). Different letters indicate significant differences ($p < 0.05$ as per Tukey test). *—values were significant at the 5% probability level.

In relation to the shade nets (Figure 4B), the highest mean plant height was found for the blue net (92.79 cm), followed by the red net (91.53 cm), black net (86.08 cm) and external environment (76.04 cm). Similar results were obtained by Mohd Yusof et al. [28] when evaluating the effect of shade nets on the growth and physiology of the medicinal plant *Polygonum minus* Huds.

The plants exposed to an EC_{ns} of 4.0 dS m^{-1} showed the greatest increment in SD (10.71 mm). The maximum increment (10.76 mm) for this variable was observed for an EC_{ns} of 3.60 dS m^{-1}. The plants exposed to 1.0 dS m^{-1} showed a 13.77% decrease in SD compared to those given the standard EC_{ns}. Under EC_{ns} levels of 3.0, 4.0 and 5.0 dS m^{-1}, there were increments of 7.21, 7.86 and 1.95%, respectively (Figure 5A).



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

Figure 5. Stem diameter (SD) of roselle plants with fertigation solutions at different electrical conductivity (**A**) and under different shade nets (**B**). Different letters indicate significant differences ($p < 0.05$ as per Tukey test). **—values were significant at the 1% probability level.

When analyzing the influence of the shade nets, it can be observed that the plants in full sun had a higher mean SD, with a value of 11.9 mm, compared to the plants under black, blue and red nets (Figure 5B).

The highest average number of leaves (158) was observed in the open air at an EC_{ns} of 3.75 dS m^{-1} (Figure 6). For the plants grown under a black net, an NL of 125 leaves was observed at an EC_{ns} of 2.99 dS m^{-1}; 102 leaves per plant under the red net was observed at an EC_{ns} of 3.39 dS m^{-1}; and under the blue net, an average count of 93 leaves was obtained at an EC_{ns} of 3.36 dS m^{-1}.

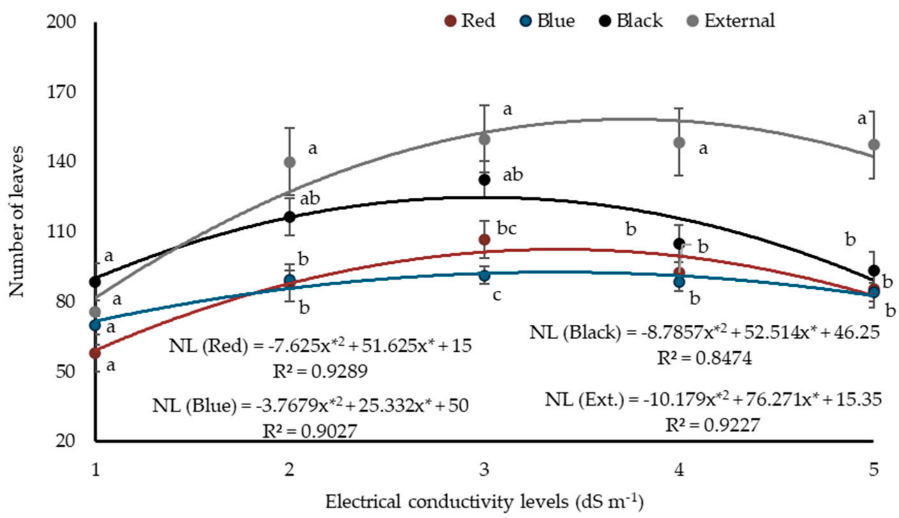


Figure 6. Number of leaves of roselle plants with nutrient solutions at different electrical conductivity and under different shade nets. Different letters indicate significant differences ($p < 0.05$ as per Tukey test). *—values were significant at the 5% probability level.

In relative terms, the number of leaves of the plants in full sun was reduced by 35.96%, with an EC_{ns} of 1.0 dS m^{-1}, compared to the salinity level of the standard solution (2.0 dS m^{-1}); and for EC_{ns} levels of 3.0, 4.0 and 5.0 dS m^{-1}, increments of 19.95, 23.90 and 11.84% were observed, respectively. When the red net was used, reductions of 32.76 and 5.98% were observed in the number of leaves, with EC_{ns} levels of 1.0 and 5.0 dS m^{-1}, respectively, and increments of 15.38 and 13.39% were observed, respectively, with EC_{ns} levels of 3.0 and 4.0 dS m^{-1}.

In the plants under the blue net and with EC_{ns} levels of 1.0 and 5.0 dS m^{-1}, the number of leaves was reduced by 16.39 and 3.66%, respectively. Under salinity levels of

3.0 and 4.0 dS m^{-1}, there were increments of 7.59 and 6.37%, respectively. Lastly, the plants shaded with the black net showed an increase of 7.39% in the number of leaves at an EC$_{ns}$ of 3.0 dS m^{-1} and reductions of 22.52, 0.34 and 23.21% with EC$_{ns}$ levels of 1.0, 4.0 and 5.0 dS m^{-1}, respectively.

The highest mean (483.75 g) of shoot fresh mass (SFM) was obtained under an EC$_{ns}$ of 3.59 dS m^{-1}. Under an EC$_{ns}$ level of 1.0 dS m^{-1}, a value of 244.19 g was obtained. For an EC$_{ns}$ of 2.0 dS m^{-1}, the observed value was 393.66 g (Figure 7A). For EC$_{ns}$ levels of 3.0, 4.0 and 5.0 dS m^{-1}, the mean values obtained were 471.46 g, 477.59 g and 412.03 g, respectively.

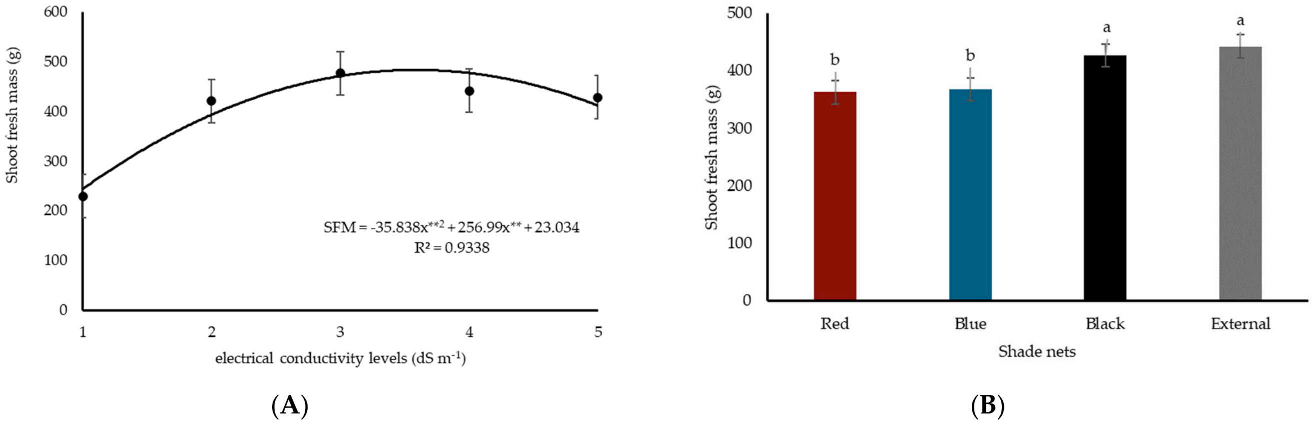


Figure 7. Shoot fresh mass (SFM) of roselle plants with fertigation solutions of different electrical conductivity (**A**) and shade nets (**B**). Different letters indicate significant differences ($p < 0.05$ as per Tukey test). **—values were significant at the 1% probability level.

The plants irrigated with a nutrient solution at an EC$_{ns}$ of 1.0 dS m^{-1} showed a reduction of 37.97% in SFM, and those at salinity levels of 3.0, 4.0 and 5.0 dS m^{-1} showed increments of 19.76, 21.32 and 4.67%, respectively.

Regarding the influence of the shade nets, the plants in the open air had a higher mean SFM, 442.14 g, compared to those under the black, blue and red nets (Figure 7B).

The highest mean shoot dry mass (SDM), 105.82 g, was obtained with a nutrient solution at an EC$_{ns}$ of 3.49 dS m^{-1}. At an EC$_{ns}$ of 1.0 dS m^{-1}, a value of 69.81 g was observed. For EC$_{ns}$ levels of 2.0, 3.0, 4.0 and 5.0 dS m^{-1}, the mean values observed were 92.92 g, 104.43 g, 104.32 g and 92.60 g, respectively (Figure 8A).

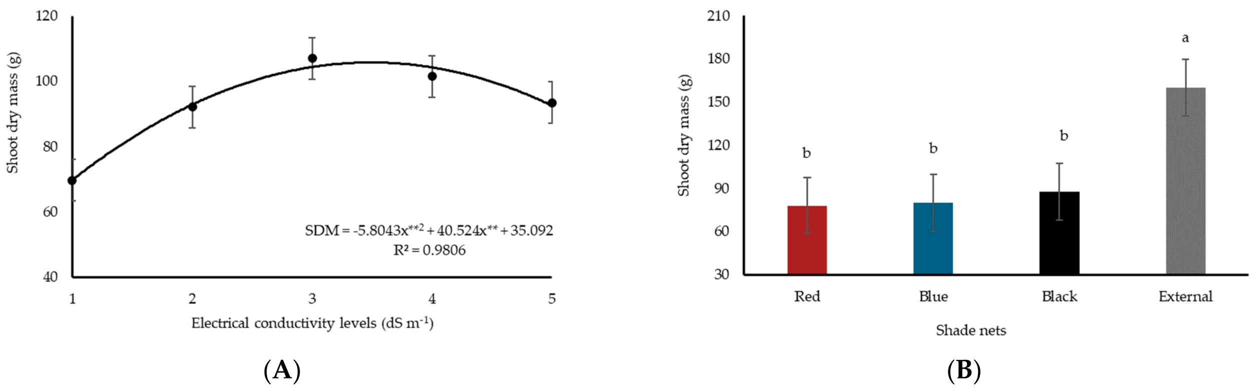
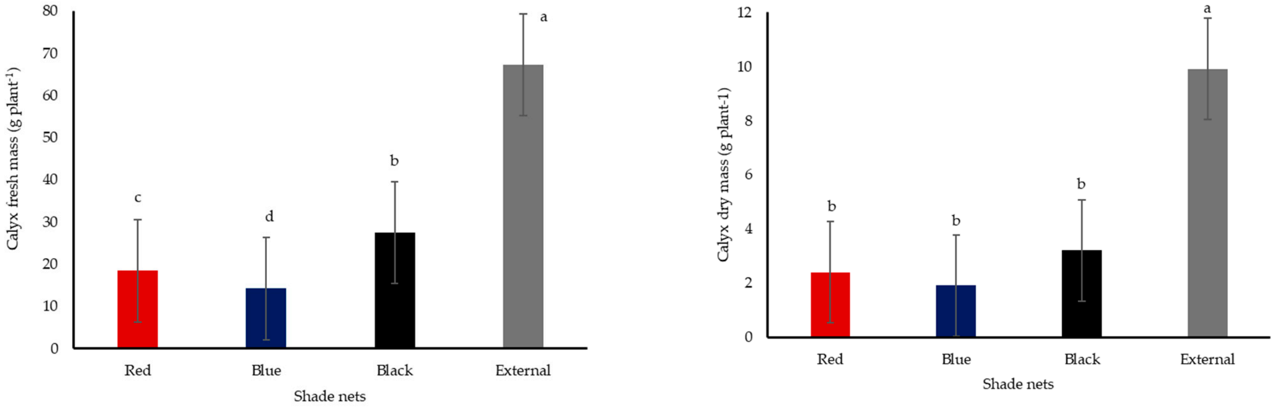


Figure 8. Shoot dry mass (SDM) of roselle plants with fertigation solutions of different electrical conductivity (**A**) and shade nets (**B**). Different letters indicate significant differences ($p < 0.05$ as per Tukey test). **—values were significant at the 1% probability level.

From another perspective, a higher value of SDM (160.11 g) was observed in the plants kept in the open air compared to those under the black, blue and red nets (Figure 8B).

Shoot dry mass was quadratically affected, with reductions of 24.87 and 0.34% with EC_{ns} levels of 1.0 and 5.0 dS m^{-1}, respectively, and increments of 12.38 and 12.26% at salinity levels of 3.0 and 4.0 dS m^{-1}, respectively.

The highest values of fresh (Figure 9A) and dry mass (Figure 9B) of the calyxes were observed in the plants grown in the open in comparison with the plants under shade nets.



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

Figure 9. Calyx fresh mass (CFM) (**A**) and calyx dry mass (CDM) (**B**) of roselle plants with nutrient solution at different levels of electrical conductivity and under different shade nets. Different letters indicate significant differences ($p < 0.05$ as per Tukey test).

In the plants subjected to the red and black nets, the number of flowers decreased under all salinity levels compared to standard salinity (Figure 10). The plants shaded with the blue net showed an increase of 7.72% in the number of flowers at an EC_{ns} of 3.0 dS m^{-1} and reductions of 25.40, 2.25 and 29.90% in the number of leaves at EC_{ns} levels of 1.0, 4.0 and 5.0 dS m^{-1}, respectively. Finally, the plants shaded in the open air showed an increase of 9.09 and 1.87% in the number of flowers at EC_{ns} levels of 3.0 and 40 dS m^{-1}, respectively, and reductions of 25.39 and 21.64% at EC_{ns} levels of 1.0 and 5.0 dS m^{-1}, respectively.

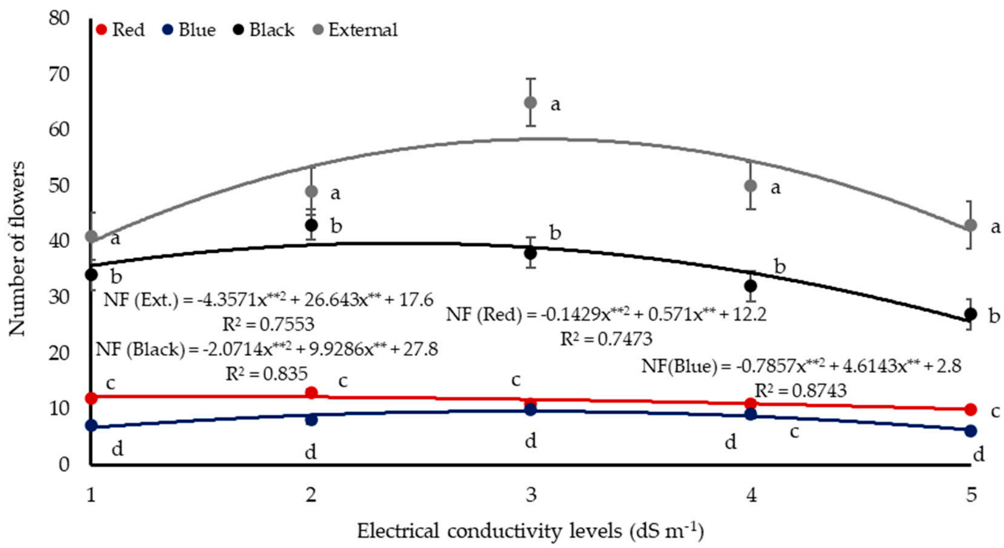


Figure 10. Number of flowers of roselle plants with nutrient solutions at different levels of electrical conductivity and under different shade nets. Different letters indicate significant differences ($p < 0.05$ as per Tukey test). **—values were significant at the 1% probability level.

4. Discussion

This study aimed to evaluate the effect of colored shading meshes and a gradual increase in the electrical conductivity of the nutrient solution on the development of *H.*

sabdariffa L. plants. Development is a phase influenced by the management of fertilization and irrigation, that is, by the proper application of fertilizers and regulation of water availability as well as by environmental factors such as temperature and relative humidity (RH). In *H. sabdariffa* L. plants, the environmental conditions of temperature, light and salinity strongly influence development from germination to maturity [29].

Temperature and RH are the main climatic factors that influence the growth, development and productivity of crops. Rising temperatures have a negative influence on plant metabolism and reduce the rate of photosynthesis [30]. When the relative humidity is within the ideal range for plants, it favors stomatal opening and closing, which optimizes gas exchange in a way that favors photosynthesis without causing excess water loss [31]. Thus, monitoring and controlling these variables in agricultural crops favor development and production, since extreme variations in temperature and humidity cause stress and reduce yield.

The changes observed in the profile of the climatic characteristics of temperature and relative humidity in the two environments are associated with the formation of a microclimate inside the greenhouse. In this environment, there is a tendency for the RH to increase during the day from the increasing amount of water vapor produced by the high transpiration rates of the plants inside the greenhouse. In contrast, the environment outside the greenhouse shows a reduction in RH and an increase in temperature due to a process that is the opposite of what happens inside the greenhouse. These effects can be increased or decreased by the wind speed and/or radiation intensity.

In this study, for the plants grown in the open, the gradual increase in EC led to significant increases in the growth and yield of calyxes up to 3.0 dS m^{-1}, with higher EC values resulting in a decrease. The highest values for plant height were observed under the red shading mesh, followed by the blue mesh. The effect of the photoprotective meshes on growth parameters proved that roselle plants need a longer photoperiod and greater light intensity to obtain a higher photosynthetic rate and greater growth and productivity.

The results showed a significant variation in plant height in response to different levels of EC_{ns}. The plant height was maximal at 3.21 dS m^{-1} (Figure 4A), suggesting that this level of electrical conductivity was most favorable for growth. The reduction in plant height at EC_{ns} levels of 1.0 and 5.0 dS m^{-1} may be associated with salt stress, which negatively affects growth. The increase observed at EC_{ns} levels of 3.0 and 4.0 dS m^{-1}, although smaller, is still notable and may be related to an adaptation of the plants to less extreme salinity conditions.

These results are consistent with previous studies, such as those by Quaresma et al. [32], which evaluated the effect of rhizobacteria in mitigating salt stress in *Hibiscus sabdariffa* L., reinforcing the importance of salinity management for optimizing plant growth. The reduction in the mean values of plant height at 3.21 dS m^{-1} and stem diameter at 3.60 dS m^{-1} is potentially related to the effects of an increase in salt stress. It is worth noting that the use of shade nets causes etiolation in the plants, which was verified by the relationship between plant height and stem diameter. In this context, it has been reported that the reduction in stem diameter in a saline environment is a response to the osmotic effect because it was observed in plants in the first days of exposure to salt stress [33].

In a study of mint under different levels of shading, it was found that >70% shading caused abnormal growth in height not accompanied by an increase in stem diameter (etiolation) as observed here, which would explain why the plants shaded by the blue and red nets were taller [34]. Thus, it is evident that the use of shade nets in a protected environment such as a greenhouse alters the distribution of solar radiation and the luminosity incident on the plants, consequently influencing their development and metabolism [35].

The differences in temperature and humidity between the covered greenhouse and the open air together with the luminosity show that biomass production was highest in the open air because the plants were under optimum photoperiod conditions. Similar results were observed by Meftahizadeh et al. [36] and Butler et al. [37] who argued that roselle delays its flowering under long photoperiod conditions. A photoperiod longer than 11 h inhibits roselle flowering [37].

In the present study, it can be stated that the number of leaves showed a greater reduction from the interaction between EC_{ns} and the blue net. The plants may have been affected by osmotic changes caused by the higher salt levels, which reduce the absorption of nutrients. In addition, the etiolation caused by the shading nets could explain the changes in stem diameter, number of leaves and biomass production. The deleterious effect of salinity was also observed in studies evaluating the development and yield of *Hibiscus sabdariffa* plants [3,38–40].

In general, colored shade nets help to achieve the highest level of plant development since they protect agricultural crops from excess temperature and luminosity [41,42]. Within this context, the red shading net can change the quality of light, especially in a controlled greenhouse environment, promoting plant growth, development and accumulation of nutrients [35].

The growth rate of plants depends on several abiotic factors, among which the light intensity clearly regulates crop growth and development because of its direct effect on photosynthesis [43]. Therefore, the use of shade nets to protect plants from excessive solar radiation can increase crop quality and yield [44]. In this context, several studies have shown that the combination of red and blue light promotes better electron excitation, which leads to greater photosynthetic activity, when compared to light of a single wavelength [45,46]. However, if the net does not have a shading level appropriate to the development of the crop, the plants will experience reductions in growth and yield, notably as observed in the present study and as reported by others [34].

Regarding the degree of salinity of the nutrient solution, the present study demonstrated that this factor negatively influenced plant height, stem diameter, number of leaves, number of flowers, shoot fresh mass and shoot dry mass above a certain threshold. These results suggest that salt stress reduces biochemical and physiological activities, consequently reducing growth and biomass [42,47]. Our study emphasizes the deleterious effects of salinity on *Hibiscus sabdariffa* plants on all the parameters studied. However, it can be inferred that the plants were able to mount a satisfactory defense to deal with the oxidative stress caused by the increase in osmotic potential because there was an increase in plant height, stem diameter, number of leaves, number of flowers, shoot fresh mass and shoot dry mass.

It is likely that the plants produced non-enzymatic antioxidants, such as phenolic metabolites and flavonoids, as a defense mechanism against abiotic stress [48]. In this regard, Bahgat [27] reported that osmotic stress caused by salinity reduced the growth of *H. sabdariffa* plants due to decreased production of proteins, carbohydrates, chlorophyll and ascorbic acid. Sheyhakinia et al. [49] concluded that the accumulation of proline and non-reducing sugars effectively improved development in hibiscus plants under saline stress due to an increase in photoassimilates and maintenance of plant water content.

As a result of the influence of photoprotective meshes on the physiology of hibiscus plants, the difference in the production of calyxes and flowers between the plants grown in the open and under shading meshes inside the greenhouse was demonstrated. Our results showed that roselle is sensitive to photoperiod, and high light intensity causes it to flower and produce fruit (Figures 9 and 10). This relationship was also verified by Butler et al. [37].

Several studies have pointed to the effect of photoperiod on plant growth and development. Similar to what happened in this study, there have been reports that photoperiod influenced plant height, stem diameter, leaf number and color of the leaves of roselle plants [50]. The photoperiod has been proven to be a factor that controls not only flowering but also seed germination, stem and leaf growth and secondary metabolism [4,51].

In addition to the salinity levels to which the roselle plants were subjected, the colored shade nets also influenced their growth and the production of fresh and dry biomass, even under conditions of low light intensity. Thus, the relationship between the results of the variables addressed is evident [27,52,53], since the reductions in stem diameter, number of leaves, number of flowers, shoot fresh mass, shoot dry mass, calyx fresh mass and calyx dry mass are associated with increased salinity and etiolation caused by shading in the protected environment with lower allocation of organic compounds [53].

5. Conclusions

Increases in the electrical conductivity of the nutrient solution to approximately 3.0 dS m^{-1} promoted increases of 2.34% in plant height, 7.21% in number of leaves, 19.76% in shoot fresh mass, 12.38% in shoot dry mass and 7.72% in number of flowers. Higher EC values resulted in a decrease. Roselle plants grown in full sun or under the black shading had increased stem diameter, fresh biomass, calyx fresh mass and calyx dry mass because of the greater light intensity. The shade nets and the salinity of the nutrient solution also influenced the number of leaves.

Under our study conditions, growing roselle in the open air proved to be the most viable from a commercial point of view, as the plants showed increased stem diameter and biomass production, indicating that they were exposed to conditions of temperature and photoperiod more favorable for increasing the rate of photosynthesis and productivity of *Hibiscus sabdariffa*.

Our data suggest that further studies should look at a 100% light factor inside the greenhouse, different levels of shading and the use of meshes on plants grown in the open and correlate this with the electrical conductivity of the fertigation solution and physical and biochemical indicators.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14102252/s1, Figure S1: Data collection, in the open air (A) and in a protected environment (B), for calibration of pyranometer sensors (mV) with the Eppley pyranometer (W m^{-2}) used as standard.; Figure S2: Linearity trend of the three pyranometers used as compared to the standard Eppley pyranometer.; Figure S3: Simplified arrangement of the irrigation system in a protected environment (A) and in the open air (B).; Figure S4: Sketch of the experimental area.

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