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The Impact of Salinity and Nutrient Regimes on the Agro-Morphological Traits and Water Use Efficiency of Tomato under Hydroponic Conditions

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Abstract: The effects of saline water on three greenhouse tomato cultivars (Feisty-Red, Ghandowra-F1, and Valouro-RZ) under three salinity concentrations (S1, ~2.5 dS m^{-1}; S2, ~6.0 dS m^{-1}; and ~9.0 dS m^{-1}) and four nutrient regimes (N1–N4) were studied by evaluating the vegetative growth, chlorophyll content, leaf area, water use efficiency (WUE), and fruit yield of the cultivars. Vegetative growth parameters, such as plant height, leaf area, and stem diameter, were negatively correlated with increased levels of salinity. Also, the lowest WUE was noted for the high-salinity (~9.0 dS m^{-1}) treatments. The Valouro-RZ cultivar performed better in terms of vegetative growth parameters when compared to both the Ghandowra-F1 and Feisty-Red cultivars. The plants grafted onto Maxifort rootstock showed more tolerance to salinity stress, with significant differences in plant growth, tomato yield, and WUE when compared with the non-grafted plants. The use of a modified nutrient solution (N2) in combination with moderately saline water (S2, ~6.0 dS m^{-1}) resulted in a high mean yield (30.7 kg m^{-2}), with a reduction of about ~1.6% compared with the mean yield of the control (i.e., the combination of S1 and N1), which was estimated to be about 31.2 kg m^{-2}. High salinity significantly affected the mean WUE, which was the highest at 31.3 kg m^{-3} for the control plants (low salinity—S1), followed by the moderate-salinity (S2) plants at 30.4 kg m^{-3}, and the lowest mean WUE was recorded for the high-salinity (S3) plants at 17.7 kg m^{-3}. These results indicate that a combination of grafting onto rootstocks and using an appropriate nutrient recipe (i.e., N2 in this study) can mitigate the negative effects of salt stress on tomato plants grown under hydroponic conditions.

Keywords: hydroponics; salinity; yield; water use efficiency

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1. Introduction

Saudi Arabia is a desertic land exposed to extreme temperatures and an arid climate, with limited groundwater resources [1]. Despite the harsh environmental conditions, such as high levels of evapotranspiration and low levels of precipitation, the Kingdom has managed to become self-sufficient in the production of some vegetables and food crop products [2]. With the rapid growth of the population, there is a rising demand for vegetables and tomatoes. Hence, the sustainability of agriculture and water resources in Saudi Arabia is essential for food and water security [3]. Soil and water resources, along with the application of agricultural inputs, determine the production potential of agricultural ecosystems. Increased crop yields are associated with an increased use of water and fertilizer, and modern research has focused on maximizing the water and fertilizer use efficiency (WFUE) of crops [3–5]. The quickly dwindling global supply of fresh water and renewable water resources, coupled with increasing demands for water from the agricultural sector, is threatening the food and water security of nations around the world. As a result, approaches to water resource management are also changing dramatically [6].

The long-term annual precipitation in Saudi Arabia is recorded as 114 mm. The annual water demand has been steadily rising due to increases in developmental activities and essential services in proportion to the growing population. The agricultural sector utilizes around 80 percent of the total quantity of water used in the Kingdom [7]. Limited water resources, sparse and low rainfall, higher temperatures, evapotranspiration, and eco-physical conditions pose significant challenges to agricultural activities. The sustainability of the agroecosystems of Saudi Arabia depends heavily on the efficient management of available soil and water resources. However, the steady decline in the finite water resources and the continued degradation of soil resources make the task much more challenging [8,9]. In addition, the external inputs required for agricultural production are becoming more scarce and costly. Thus, the conservation of water and soil resources via the transformation of traditional agricultural practices into modern agricultural practices for self-sustainability is an essential matter in Saudi Arabia. The construction of greenhouses and protected cultivations alter microclimate conditions to favor the productivity of plants, and they also predominantly reduce transpiration and increase water productivity [10,11].

In traditional agriculture, soil is a medium of plant growth that offers mechanical support to plants, stores water, and provides plants with the required nutrients. However, continuous and intensive use of soil in greenhouses has led to infestation by plant pathogens and deficiencies in essential nutrients. This has resulted in the use of soil disinfections, leading to the pollution of the environment and damage to fertigation systems [12]. Hydroponics, a smart agricultural technique involving the cultivation of plants without soil, which is also referred to as soilless culture and nutriculture, among other terms, is a viable system that overcomes these problems [13,14]. The production of crops in hydroponic greenhouses results in increased food production, improved food quality, conservation of resources, and protection of the environment. In Saudi Arabia, water is not only scarce but also precious. Since saline water can be used as an alternative for irrigating salt-tolerant crops, especially under hydroponic conditions, the country is planning to use desalinated sea (saline) water as an alternative to groundwater resources [15,16]. In such a situation, studies on the use of saline water without sacrificing the yield and quality of crops are very much necessary to determine appropriate water management practices.

In general, to achieve optimum yields regardless of the substrate used, plants must be supplied with an adequate amount of a nutrient solution to compensate for high evapotranspiration rates and to ensure an adequate source of nutrients, along with the draining of excess amounts of nutrients and ensuring the availability of oxygen to the root system to avoid the accumulation of salt in the root zone [17–19]. Plants exposed to high concentrations of salt experience osmotic stress, which leads to water deficits and unhealthy growth. These factors negatively affect the physiological and metabolic processes of plants, such as photosynthesis, respiration, and cell division [20–23]. The accumulation of sodium (Na^+) and chloride (Cl^-) in plants prevents the intake of nutrients (K^+, Ca^{++}, Mg^{++}, and NO^{3-}) and leads to reductions in vegetative growth and yield [24,25].

Crops that can be hydroponically grown with saline water are limited to salt-tolerant and moderately salt-tolerant species, such as tomato, asparagus, cucumber, rose, and carnation. Even among salt-tolerant species, varietal differences may exist. Varietal trials need to be conducted to determine the most tolerant varieties. The salt tolerance of a variety, its stage of development, the frequency of irrigation, and the addition of deficit nutrients are several factors to be considered when using saline water. Tomato plants have been reported to be a moderately salt-tolerant crop [26–28]. In previous research, salt stress was found to result in reduced growth and yield. However, salt stress produced fruits of better quality, which fetched higher market prices [29–32]. Tomato has been characterized as salt-sensitive and reported to be more susceptible to high salinity (8.7 dS m^{-1}) at an early stage of development than in late growth stages [31]. However, Li et al. [33] observed that the effects of salt stress could be fully revocable by discharging excess amounts of salt from tomato roots, provided that the plant parts have not attained the rapid growth stage at a salinity level of 9.0 dS m^{-1}.

Therefore, this study aimed (i) to assess the effects of salinity on three tomato cultivars grown under hydroponic conditions on perlite substrate by examining the morphological features (plant height, stem diameter, and leaf area), mineral concentrations in plant tissues (chlorophyll, Na^+, Ca^{2+}, and K^+), fruit size, and yield, and (ii) to evaluate the effect of grafting for alleviating the effects of salinity and the water use efficiency (WUE) of these tomato crops, induced by three salinity levels (EC values of ~2.5, ~6.0, and ~9.0 dS m^{-1}) and four nutrient solutions (N1–N4).

2. Materials and Methods

Experimental trials were conducted across two seasons, 2020–2021 and 2021–2022, in a hydroponic greenhouse (28 × 32 × 4.5 m) at the educational farm (24°39′ N, 46°44′ E) of the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia. To control the indoor climate and hydroponic irrigation system, the greenhouse was equipped with MACQU systems (Geosmart, Athens, Greece) to implement the planned treatments. The climate system was equipped with cooling pads and fans, heaters, circulation fans, shading screen, and overhead ventilation, along with sensors installed at a height of 2.0 m inside the greenhouse to monitor radiation, temperature, and relative humidity. Tomato plants were grown on 12 lines of stainless-steel troughs at a height of 1 m with a slope of 5%. Each experimental line accommodated 27 perlite substrate bags (0.90 × 0.22 × 0.15 m), each with a capacity of 30 L. The distance between two plant lines was 1.78 m, and the distance between two plants within a line was 0.25 m. The plant density was maintained at 2.7 plants m^{-2}. Irrigation was performed using self-draining drippers set at a flow rate of 3 L h^{-1}, with a weekly schedule in an open operation mode. The irrigation water had an EC value of 1.04 dS m^{-1} and Na^+, Ca^{2+}, K^+, HCO_3^-, Cl^-, and SO_4^- content of 3.61, 0.76, 0.19, 0.35, 2.39, and 1.82 meq L^{-1}, respectively.

2.1. Plant Materials, Growth Conditions, and Experimental Setup

Three commercial greenhouse tomato (*Solanum lycopersicum* L.) cultivars, Ghandowra-F1 (Enza Zaden, Enkhuizen, The Netherlands), Valouro-RZ (Rijk Zwaan, De Lier, The Netherlands), and Feisty-Red (Seminis, St. Louis, MO, USA) were used as scions. The selected scion cultivars were grafted onto a commercial rootstock, Maxifort (*S. lycopersicum* × *S. habrochaites*, De Ruiter Seeds/Monsanto, Bergschenhoek, The Netherlands). Non-grafted plants of the three tomato cultivars were used as the control. Tomato rootstocks and scion seedlings with identical stem diameters at similar growth stages were selected for grafting. To ensure similar stem diameter and differences in growth vigor, the rootstock seeds were sown five days earlier than the seeds of the scions [34–36]. A tube grafting technique was adopted, and the grafted seedlings were kept at controlled conditions at a temperature between 22 °C and 24 °C and a relative humidity of 85–90%, with 45% shade, for seven days for their better survival [37]. Healthy seedlings of grafted and non-grafted tomatoes were transplanted into a hydroponic glass greenhouse at the four-leaf stage on 6 February 2020 (1st season) and 25 November 2020 (2nd season).

The experiments were conducted in both seasons using a split-split-plot system and a randomized complete block design with three replicates. Three salinity levels designed as low (~2.5 dS m^{-1}), moderate (~6.0 dS m^{-1}), and high (~9.0 dS m^{-1}) and four nutrient recipes (N1–N4) were used in both the first and second seasons (Table 1). The control nutrient solution (N1) was prepared with water-soluble fertilizers, as recommended by Hochmuth and Hochmuth [38]. The rest of the nutrient recipes (N2–N4), as presented in Table 2, were prepared by adding more concentrations of K and Ca to the control recipe (N1), where N2 was N1 + 15% additional amount of K, N3 was N1 + 15% additional amount of Ca, N4 was N1 + 15% additional amount of both K and Ca. The EC of the fertilizer solution was maintained at ~2.0 dS.m^{-1} for each salinity level. In the case of salinity level S1, municipality-supplied water with an EC of ~1.0 dS.m^{-1} was used and the N1 solution was prepared with an EC of ~3.0 dS.m^{-1}. In the case of the S2 and S3 treatments, an EC of 2 dS.m^{-1} was maintained for the fertilizer recipe, and the EC of the solutions was adjusted with added NaCl dissolved in municipality-supplied water to a final value of ~6.0 and ~9.0 dS.m^{-1}, respectively. To prevent possible osmotic shock, NaCl concentration was initiated at 20 mM and then gradually increased until reaching the targeted concentration, as described in [39]. The pH and EC of the nutrient solutions were monitored frequently using hand-held pH and EC devices.

Table 1. Salinity (S) and nutrient solution (N) used in the experiments across the two growing seasons.

		EC (dS m^{-1}) of Irrigation Solutions			
Salinity	**Nutrient Solution**	**Irrigation Water**	**Fertilizer (±0.2)**	**Added NaCl (mM)**	**Final EC (±0.2)**
S1	N1	0.92	1.6	0	~2.5
S1	N2	0.92	1.8	0	~2.5
S1	N3	0.92	1.8	0	~2.5
S1	N4	0.92	1.8	0	~2.5
S2	N1	0.92	1.6	30	~6.0
S2	N2	0.92	1.8	30	~6.0
S2	N3	0.92	1.8	30	~6.0
S2	N4	0.92	1.8	30	~6.0
S3	N1	0.92	1.6	60	~9.0
S3	N2	0.92	1.8	60	~9.0
S3	N3	0.92	1.8	60	~9.0
S3	N4	0.92	1.8	60	~9.0

Table 2. Nutrient solution [38] used as a control (N1) in the experiments across the two growing seasons.

Nutrient (ppm)	**Growth Stage**				
	Transplant to 1st Cluster	**1st Cluster to 3rd Cluster**	**3rd Cluster to 5th Cluster**	**5th Cluster to 7th Cluster**	**7th Cluster to Termination**
N	70	80	100	120	150
P	50	50	50	50	50
K	120	120	150	150	200
Ca	150	150	150	150	150
Mg	40	40	40	50	50
S	50	50	50	60	60
Fe	2.8	2.8	2.8	2.8	2.8
Cu	0.2	0.2	0.2	0.2	0.2
Mn	0.8	0.8	0.8	0.8	0.8
Zn	0.3	0.3	0.3	0.3	0.3
B	0.7	0.7	0.7	0.7	0.7
Mo	0.05	0.05	0.05	0.05	0.05

Note: Ca, Mg, and S concentrations vary according to their concentrations in the irrigation water. Sulfuric acid was used for acidification (1 ppm = 1 mg/L).

A programmed irrigation schedule was prepared to supply the nutrient solutions to the plants. The schedule was set based on the incoming solar radiation, plant transpiration demands, and growth stage. The "irrigation start mode" was set at an accumulated radiation threshold of 400 flux, and the "irrigation stop mode" was set based on attaining the selected dose [40]. The nutrient concentration of each solution was tested for EC and pH on a daily basis. The pH range was set from 5.5 to 6.5, and the targeted EC and pH values were adjusted by adding acidic and sodic solutions, without affecting the target nutrient concentrations [41,42]. The nutrient solutions were supplied to the plants through drippers for two (initial plant growth stage) to eight minutes (maturity stage) for 2 to 5 times a day using automatically activated motor pumps. In the summer months, more water was supplied twice during the nighttime, at 11 p.m. and at 2 a.m. (3 min each) when the temperature exceeded 30 °C. The drainage percentage of the nutrient solutions was maintained at 10–15% [38]. An automatic climatic controller was used to maintain the threshold air temperature at 22 °C and 18 °C during daytime and nighttime, respectively.

2.2. Data Collection and Statistical Analysis

Tomato plant growth parameters (plant height, leaf area, and stem diameter) and leaf chlorophyll measurements were collected at days 25, 50, 75, and 110 after transplanting (DAT) and the data were summed for the entire season. The use of non-destructive methods provides a cost-efficient means for frequent measurements of leaf chlorophyll over a large area. Previous studies have found that spectral indices derived from light absorption or reflection in the visible and near-infrared (NIR) regions have good correlations with leaf chlorophyll. A portable chlorophyll meter (SPAD-502/501, Soil Plant Analysis Development, Konica–Minolta, Inc., Osaka, Japan) was used to measure the chlorophyll content of the plants by taking measurements with eight readings between the midrib and the leaf margin. Since the SPAD meter readings were relative quantities, they were converted to actual leaf chlorophyll content using the generalized transformation equations developed by Cerovic et al. [29].

Tissue analysis was performed to determine the Na^+, K^+, and Ca^{2+} concentrations in leaf petioles. Tomatoes were harvested when at least 80% of the fruits attained the red ripeness stage. The harvested fruits were weighed and graded. The unmarketable yield represented fruits exhibiting cracking, catface, blossom-end rot, blotchy ripening, and fruits that fell into the category of extra-small-sized (<40 mm). The collected data were analyzed using the SAS software program (Version 9.4, SAS Institute Inc. Cary, NC, USA). Significant differences among the individual treatments were evaluated using an analysis of variance (ANOVA) and the least significant difference (LSD) test. The collected data from the experiments were subjected to a tri-factorial ANOVA (salinity × nutrition × block) with nutrient and salt treatments as the main factors. In addition, a principal component analysis (PCA) was performed to determine the biophysical parameters that were responsive to salinity stress.

3. Results

3.1. Vegetative Growth

As shown in Table 3, the morphological features, such as plant height, stem diameter, and leaf area, of the tomato plants were highly affected when the plants were grown under high-salinity treatment (S3) compared with low-salinity treatment (S1, ~3.0 dS m^{-1}). A significant impact of salinity on tomato plant height was observed across the implemented treatments (Figure 1). The mean plant height reached a maximum value of 193.6 cm under the low-salinity (S1, ~2.5 dS m^{-1}) treatment, and a minimum height of 126.9 cm was observed for the high-salinity treatment (S3, ~9.0 dS m^{-1}). A similar trend was noted with regard to stem diameter and leaf area. At a low-salinity level (S1), the leaf area was recorded as 16 m^2 $plant^{-1}$, which was 40.3% higher than the leaf area (11.4 m^2 $plant^{-1}$) recorded at S3 salinity level (EC~9.0 dS m^{-1}). A lower (10.2 mm) value of stem diameter was observed when the plants were treated at S3 salinity level, which was 36.2% higher compared with the control (S1) treatment. Overall, the moderate salinity (S2) treatment was found to be on par with the S1 treatment with respect to morphological features. Moreover, the mean difference in the value of leaf area and stem diameter across the first and second seasons was 19% and 22%, respectively, under low-salinity water treatment.

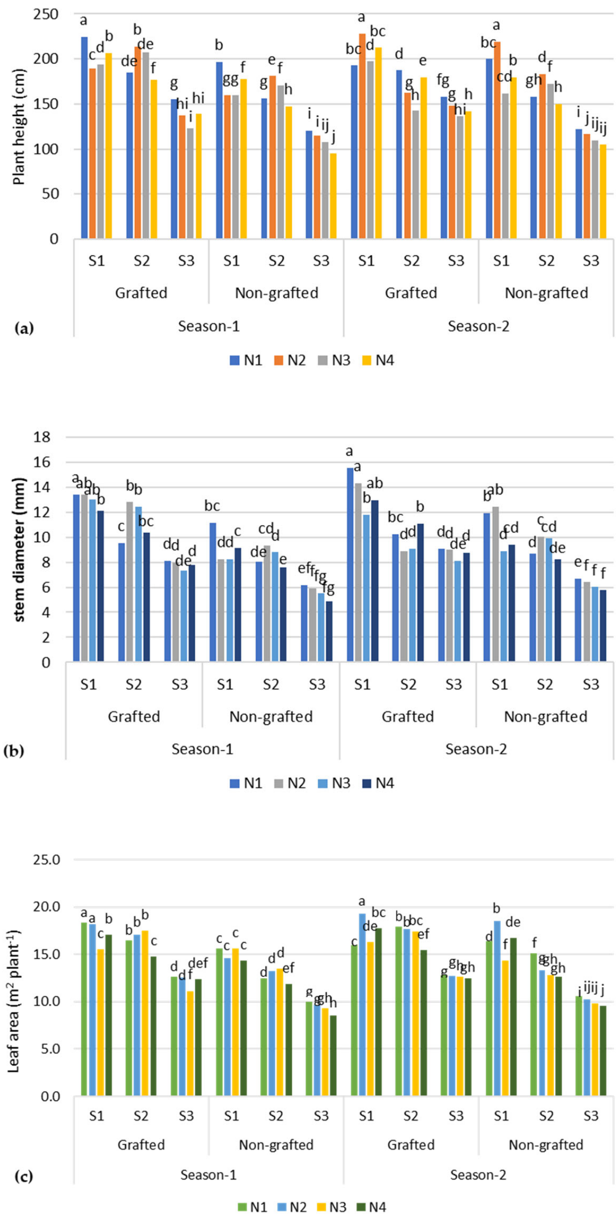


Figure 1. Morphological parameters of tomato plants under different salinity (S) stress and nutrient recipes (N): (**a**) tomato plant height, (**b**) stem diameter, and (**c**) leaf area.; The columns with different lowercase letters are significantly different ($p < 0.05$).

The responses of the plants in terms of morphological parameters to the tested nutrient recipes N1 and N2 produced more or less the same values. A maximum plant height of 171.3 cm was obtained for N2, which was 11% higher compared with the control (N1). This was followed by N3 (160.4–153.3 cm) and N4 (157–161.3 cm). The maximum stem diameter reached up to 12.7 mm in the control (N1), while reductions of 2.4%, 3.6%, and 7.2% in stem-diameter values were observed for the N2, N3, and N4 recipes, respectively. Unlike stem diameter, leaf area was found to be superior at 14.5 m^2 plant^{-1} in plants treated with N1 and N2, and a slight reduction was observed for the N3 (14.2 m^2 plant^{-1}) and N4 (13.8 m^2 plant^{-1}) -treated plants. The results for season 1 showed that the vegetative growth parameters, including plant height, stem diameter, and leaf area, were moderately significantly higher (P = 0.03) under a combination of moderate salinity (S2) and N2 recipe compared with other treatments, but they were not superior to the control (i.e., combination of S1 and N1). However, in season 2, the mean vegetative growth parameters were somewhat superior to the control (N1) but comparable to the S1 treatments. The results also indicated that the performance of the grafted plants was better than the non-grafted plants.

Table 3. Responses of tomato crops grown under different salinity and nutrient treatments.

Treatments	Plant Height (cm)			Stem Diameter (mm)			Leaf Area (m^2 $plant^{-1}$)		
	Season 1	Season 2	Mean	Season 1	Season 2	Mean	Season 1	Season 2	Mean
(a) Salinity level									
S1 (~2.5 dS m^{-1})	188.5 ^{a}	198.7 ^{a}	193.6	13.7 ^{a}	14.1 ^{a}	13.9	15.9 ^{a}	16.0 ^{a}	16.0
S2 (~6.0 dS m^{-1})	179.7 ^{a}	166.9 ^{b}	173.3	12.3 ^{b}	13.1 ^{a}	12.7	14.8 ^{b}	15.9 ^{b}	15.4
S3 (~9.0 dS m^{-1})	124.1 ^{b}	129.6 ^{c}	126.9	10.6 ^{c}	9.8 ^{b}	10.2	11.0 ^{c}	11.8 ^{c}	11.4
(b) Nutrient recipe									
N1 (control)	173.0 ^{a}	169.6 ^{a}	171.3	12.1 ^{a}	12.7 ^{a}	12.4	14.2 ^{a}	14.7 ^{a}	14.5
N2 (N1 + 15% K)	166.0 ^{a}	176.1 ^{a}	190.1	12.2 ^{a}	12.8 ^{a}	12.5	14.3 ^{a}	14.8 ^{a}	14.6
N3 (N1 + 15% Ca)	160.4 ^{b}	153.3 ^{b}	156.9	11.6 ^{b}	12.6 ^{a}	12.2	13.4 ^{b}	14.9 ^{a}	14.2
N4 (N1 + 15% K + Ca)	157.0 ^{b}	161.3 ^{b}	159.2	11.4 ^{b}	12.1 ^{b}	11.8	13.7 ^{b}	13.8 ^{b}	13.8
(c) Grafting									
GR (Grafted)	179.3 ^{a}	173.9 ^{a}	176.3	13.3 ^{a}	13.6 ^{a}	13.5	15.1 ^{a}	15.7 ^{a}	15.4
NG (Non-grafted)	149.1 ^{b}	156.2 ^{b}	152.6	10.4 ^{b}	11.6 ^{b}	11.0	12.6 ^{b}	13.5 ^{b}	13.1
(d) Tomato cultivars									
Valouro-RZ	154.8 ^{c}	156.5 ^{c}	155.7	11.4 ^{b}	12.1 ^{b}	11.8	133.6 ^{b}	138.9 ^{c}	136.3
Ghandowra-F1	163.3 ^{b}	165.2 ^{b}	164.3	11.8 ^{b}	12.6 ^{a}	12.2	138.5 ^{b}	147.1 ^{b}	142.8
Feisty-Red	176.1 ^{a}	177.8 ^{a}	177.0	12.3 ^{a}	13.1 ^{a}	12.7	144.5 ^{a}	152.7 ^{a}	148.6

Note: The values with different superscript letters in a column are significantly different ($p < 0.05$).

3.2. Fruit Yield

The results of this study showed that there were significant differences in the yields of tomato fruits among different salt concentration levels (S) and nutrient recipes (N). As depicted in Table 4, the highest fruit yield (27.6 kg m^{-2}) was recorded for the low-salinity (S1, ~2.5 dS m^{-1}) treatment, and the fruit yield reduced to 15.6 kg m^{-2} when the plants were treated with the high-salinity (S3, ~9.0 dS m^{-1}) treatment (Table 3). As illustrated in Figure 2, the tomato fruit yield (26.8 kg m^{-2}) of the plants treated with moderate salinity stress (~6.0 dS m^{-1}) was comparable to the yield of the S1 treatment, accounting for a reduction of 2.8% in yield. The plants treated with the N1 recipe produced a higher yield (24.2 kg m^{-2}), followed by the N2 (23.8 kg m^{-2}), N3 (23.1 kg m^{-2}), and N4 (22.3 kg m^{-2}) recipes. The total fruit yields of the grafted (GR) and non-grafted (NG) plants were significantly different. The GR plants recorded a mean of 25.2 kg m^{-2} and 25.9 kg m^{-2} for season 1 and season 2, respectively. In contrast, the mean yield of the NG plants ranged between 21.7 kg m^{-2} (season 1) and 20.5 kg m^{-2} (season 2), with a difference of 19.7%. Under high-salinity conditions (~9.0 dS m^{-1}), the GR plants produced 18.5 kg m^{-2} of tomatoes, accounting for a higher yield of 23% compared with the NG (12.8 kg m^{-2}) plants (Figure 2). On the other hand, a yield difference of 37.5% between the GR and NG plants was observed under low-salinity water (S1) treatment.

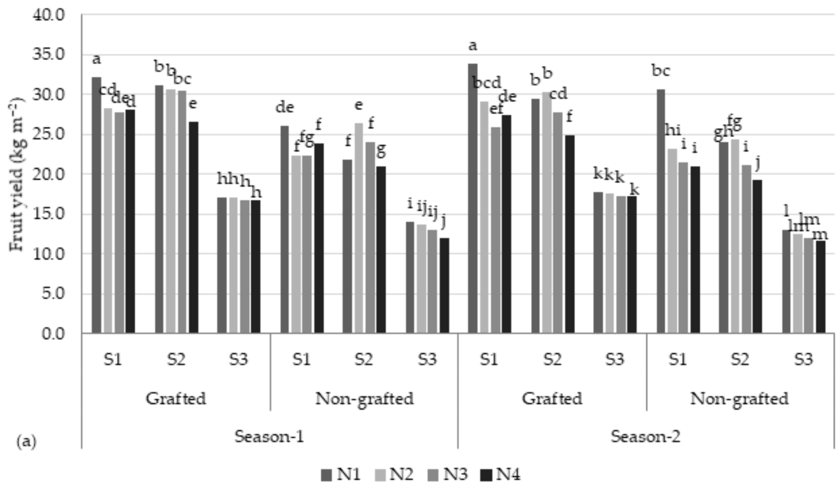
3.3. Water Use Efficiency

In contrast, as illustrated in Table 4 and Figure 2, the obtained WUE (computed by dividing the tomato fruit yield (kg m^{-2}) with the amount of nutrient solution utilized for irrigation in m^3 m^{-2}) of the tomato crops varied significantly across the salinity treatments. The highest WUE (31.3 kg m^{-3}) was recorded under the low-salinity conditions (S1), and the value was low under the high-salinity conditions (S3). These findings agree with Lovelli et al. [28], who found that the WUE of eggplant increased with increasing salinity stress. These results imply that tomato plants can perform better under low-salinity (S1) to moderate-salinity (S2) conditions, and that it is viable to utilize low to moderate saline water in a proportion of the nutrient solution as irrigation water in hydroponics to improve WUE [29]. This study also confirmed that moderate saline water is an alternative for tomato production under hydroponic conditions throughout a growing season to achieve an acceptable yield (31.3–30.4 kg m^2).

Table 4. Response in terms of tomato yield and water use efficiency (WUE) to different salinity and nutrient treatments.

Treatments	Fruit Yield (kg m^{-2})			WUE (kg m^{-3})		
	Season 1	Season 2	Mean	Season 1	Season 2	Mean
(a) Salinity level						
SI (2.5 dS m^{-1})	26.4 ^{a}	28.8 ^{a}	27.6	30.2 ^{a}	32.3 ^{a}	31.3
S2 (6.0 dS m^{-1})	26.3 ^{a}	27.2 ^{a}	26.8	29.4 ^{b}	31.4 ^{b}	30.4
S3 (9.0 dS m^{-1})	15.2 ^{b}	15.9 ^{b}	15.6	16.9 ^{c}	18.4 ^{c}	17.7
(b) Nutrient recipe						
N1 (control)	23.6 ^{a}	24.8 ^{a}	24.2	26.3 ^{a}	28.4 ^{a}	27.4
N2 (N1 + 15% K)	22.7 ^{b}	24.9 ^{a}	23.8	25.9 ^{b}	28.0 ^{b}	27.0
N3 (N1 + 15% Ca)	22.6 ^{c}	23.5 ^{b}	23.1	25.9 ^{b}	26.5 ^{c}	26.2
N4 (N1 + 15% K + Ca)	21.8 ^{d}	22.7 ^{c}	22.3	24.9 ^{c}	25.6 ^{c}	25.3
(c) Grafting						
GR (Grafted)	25.2 ^{a}	25.9 ^{a}	25.6	28.6 ^{a}	29.4 ^{a}	29.0
NG (Non-grafted)	21.7 ^{b}	20.5 ^{b}	21.1	24.6 ^{b}	23.3 ^{b}	24.0
(d) Tomato cultivars						
Valouro-RZ	23.2 ^{a}	23.9 ^{a}	23.6	29.2 ^{a}	30.3 ^{a}	29.8
Ghandowra-F1	23.5 ^{a}	23.5 ^{a}	23.5	26.5 ^{b}	27.0 ^{b}	26.8
Feisty-Red	23.7 ^{a}	22.3 ^{b}	23.0	24.7 ^{c}	24.8 ^{c}	24.8

Note: The values with different superscript letters in a column are significantly different ($p < 0.05$).



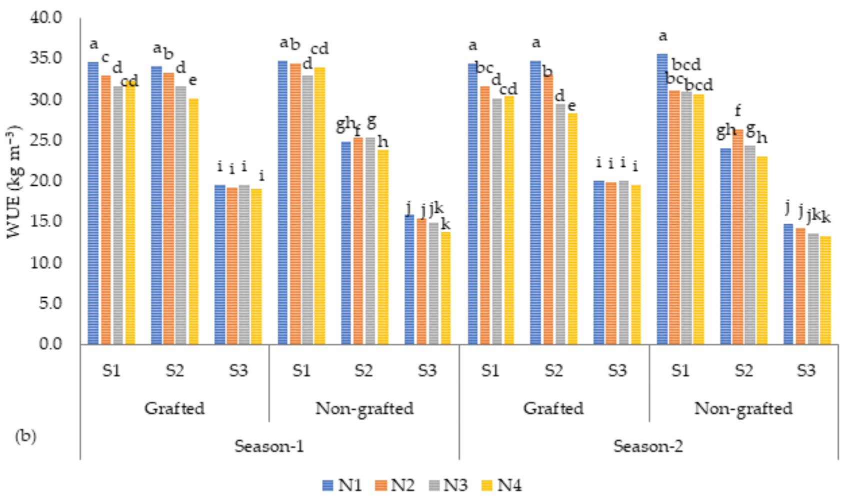


Figure 2. (**a**) Tomato fruit yield and (**b**) water use efficiency (WUE) under different salinity (S) stress conditions and nutrient recipes (N). The columns with different lowercase letters are significantly different ($p < 0.05$).

3.4. Chlorophyll and Ion Concentrations in Plant Tissues

The leaf tissue analysis revealed that the chlorophyll content (SPAD) and tested ion concentrations (Na^{+}, Ca^{2+}, and K^{+}) significantly varied across the different saline water treatments (Table 5). The chlorophyll content of the plants treated with the low-salinity (S1) water treatment was 56–58%, accounting for a higher level of ~36% in chlorophyll content compared with the plants treated with the S3 water treatment (37%). As illustrated in Table 5, the concentrations of Ca^{2+} and K^{+} followed similar trends. Higher ion concentrations were observed for the plants under the low-salinity (S1) treatment compared with the S3 plants. In the case of Na^{+}, the leaf tissue analysis showed low amounts of Na^{+} (0.14%) in the plants under the high-salinity (S3) treatment compared with the S1 plants (0.21%). There was a slight difference in tested ion concentrations among the nutrient (N) treatments. The ion concentrations were higher under the N1 and N2 treatments compared with the N3 and N4 treatments. In the case of grafted and non-grafted plants, the GR plants had higher ion concentrations than the NG plants. When plants are exposed to higher salt concentrations, the plants become over-salted due to the osmotic effect in the roots, thus restricting their intake of water and causing a water deficit in the plants, which is detrimental to growth. As a result of the increased buildup of Cl^{-} and N^{+}, plants start to experience phytotoxicity and are re-blocked from absorbing certain nutrients (i.e., leading to nutritional imbalances) [8,9]. These elements have an adverse effect on the physiological and metabolic functions of plants, including cell division, respiration, and photosynthesis [10–13], all of which lead to a decrease in vegetative growth and crop yield.

Table 5. Influence of salinity (S) and nutrient recipe (N) treatments on leaf chlorophyll and mineral composition: salinity stress, nutrient recipe, grafted condition, and tomato cultivars.

Treatments	Chlorophyll (g)		Na^{+} (%)		Ca^{2+} (%)		K^{+} (%)	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
(a) Salinity								
S1	56.4 ^{a}	58.1 ^{a}	0.22 ^{a}	0.20 ^{a}	1.71 ^{a}	1.76 ^{a}	3.41 ^{a}	3.53 ^{a}
S2	47.4 ^{b}	48.8 ^{b}	0.16 ^{b}	0.17 ^{b}	1.53 ^{b}	1.52 ^{b}	3.01 ^{b}	3.05 ^{b}
S3	36.2 ^{c}	37.3 ^{c}	0.11 ^{b}	0.14 ^{b}	1.44 ^{c}	1.41 ^{c}	2.69 ^{c}	2.75 ^{c}
(b) Nutrient recipe								
N1	48.1 ^{a}	49.2 ^{a}	0.12 ^{a}	0.18 ^{a}	1.62 ^{a}	1.63 ^{a}	3.35 ^{a}	3.38 ^{a}
N2	47.8 ^{a}	49.2 ^{a}	0.14 ^{a}	0.17 ^{a}	1.53 ^{b}	1.54 ^{b}	3.21 ^{b}	3.22 ^{b}
N3	45.6 ^{a}	46.9 ^{a}	0.17 ^{b}	0.17 ^{a}	1.52 ^{b}	1.42 ^{b}	2.96 ^{b}	3.03 ^{b}
N4	45.5 ^{a}	46.8 ^{a}	0.15 ^{b}	0.16 ^{b}	1.41 ^{c}	1.38 ^{c}	2.62 ^{c}	2.71 ^{c}
(c) Grafting								
Grafted	48.7 ^{a}	50.1 ^{a}	0.18 ^{a}	0.17 ^{a}	1.61 ^{a}	1.57 ^{a}	3.93 ^{a}	3.18 ^{a}
Non-grafted	41.7 ^{b}	43.2 ^{b}	0.13 ^{b}	0.12 ^{b}	1.46 ^{b}	1.43 ^{b}	3.28 ^{b}	3.04 ^{b}
(b) Cultivars								
Valouro-RZ	47.8 ^{a}	49.2 ^{a}	0.14 ^{b}	0.16 ^{a}	1.53 ^{b}	1.52 ^{a}	3.23 ^{a}	3.22 ^{a}
Ghandowra-F1	45.6 ^{a}	46.9 ^{a}	0.17 ^{a}	0.16 ^{a}	1.62 ^{a}	1.61 ^{a}	3.37 ^{a}	3.38 ^{a}
Feisty-Red	38.4 ^{b}	39.2 ^{b}	0.12 ^{b}	0.14 ^{b}	1.52 ^{b}	1.42 ^{b}	2.96 ^{b}	3.03 ^{b}

Note: The values with different superscript letters in a column are significantly different ($p < 0.05$).

4. Discussion

All the tested morphological parameters with respect to salinity and grafting treatments were found to be highly significant in both season 1 and season 2. The plants under the low-salinity (S1) treatment and the grafted plants performed well, and the S2 treatment could be considered as its effects are on par with the S1 treatment. These findings are in agreement with the recent results reported by Zhang et al. [30], who found that fruit yield was not significantly affected under moderate-salinity conditions (~6.0 dS m^{-1}), implying that the use of moderately saline (NaCl) water for irrigation may not decrease fruit yield at a significant level. The mean of total fruit yield for both grafted and non-grafted tomato cultivars, as shown in Figure 2, indicated that growing tomato plants under salinity levels of up to 6.0 dS m^{-1} (S2) resulted in no significant differences (LSD = 1.167 kg m^{-2}), where the average total yield under S1 was 27.6 kg m^{-2} compared with 26.8 kg m^{-2} under S2. However, the average total fruit yield under S3 (15.6 kg m^{-2}) was significantly lower compared with that under both S1 and S2. The WUE results followed the same trend of total fruit yield. The mean WUE showed significant differences under different salinity levels, with the WUE under S1 conditions (31.3 kg m^{-3}) being the highest, followed by that under S2 conditions (30.4 kg m^{-3}). However, the mean WUE under S3 conditions (17.7 kg m^{-3}) was significantly lower compared with that under both S1 and S2 conditions. The results of grafted and non-grafted Ghandowra-F1 plants showed a significant decrease in total fruit yield with an increase in salinity concentration. With respect to nutrient (N) recipes, the impact on total fruit yield was not significant. However, N1 and N2 were found to have better effects compared with other recipes, with LSD of 1.167 and 1.190 kg m^{-2} for the first and second seasons, respectively. These results showed that all studied tomato cultivars could be grown successfully under hydroponic systems using irrigation water with salt concentration up to 6.0 dS m^{-1} in combination with the N1/N2 recipe without affecting total fruit yield.

The results shown in Tables 6 and 7 indicate that grafted plants tolerated salinity stress better than non-grafted plants, as evidenced by the higher vegetative growth and yield under high-salinity conditions (i.e., ~9.0 dS m^{-1}). The increase in WUE was clearly observed in the grafted cultivars, whose WUE under the low-salinity (S1) conditions was greater by 42–47.0% (for non-grafted plants) and 50–55.1% (for grafted plants) compared with those under the high-salinity conditions (S3). Similar results were reported by Patane et al. [42], who found that the difference in the WUE of tomato cultivars with respect to salinity treatments ranged between 2 and 15 dS m^{-1}, which was less evident than in the present study. Another study [43] also confirmed that irrigation of tomato plants with moderate saline water could be more efficient.

Table 6. Analysis of variation (ANOVA) (mean square) examining agro-morphological traits in tomato plants under different salt stress (S), nutrient (N) recipe, and grafting conditions (season 1).

Parameter	Pr > F				
	Yield	WUE	Plant Height	Stem Diameter	Leaf Area
Salinity (S)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Nutrient (N)	0.045	0.045	0.085	0.335	0.333
Grafting (G)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
S*N	<0.0001	<0.0001	0.040	0.031	0.001
S*G	0.163	0.163	0.168	0.504	0.086
N*G	0.705	0.705	0.595	0.260	0.462
S*N*G	0.001	0.001	0.849	0.963	0.036
R^2	0.962	0.962	0.901	0.876	0.896
Coeff. Var.	8.49	8.49	7.38	10.05	9.78
RMSE	1.98	2.25	16.13	1.23	1.39
Mean	23.36	26.48	218.46	12.23	14.25
LSD	1.167	1.32	9.48	0.72	0.82

Moreover, the nutrient recipe N2 was superior under salinity stress compared with the N3 and N4 recipes due to its higher performance in terms of vegetative growth and yield parameters. Also, higher WUE values were recorded in Maxifort-grafted tomato plants compared with non-grafted plants under the low-salinity level (S1). Moreover, non-grafted plants grown under the S1 treatment showed the lowest plant growth and yield values (Table 4). These results support the results of Schwarz et al. [44], who found that grafting tomato plants onto an appropriate rootstock reduces crop yield losses under salinity stress.

Grafting Valouro-RZ and Ghandowra-F1 cultivars onto Maxifort significantly improved their growth and yield parameters (Table 8). This is because plants grafted onto a suitable rootstock are able to absorb more water and nutrients from the root zone than non-grafted plants due to their robust root structure, which increases the contents of endogenous plant hormones and, thus, the rate of photosynthesis, which in turn enhances plant growth and fruit development [30,31]. Distinct variations in plant growth and fruit yield were observed among the studied tomato cultivars due to the applied salinity treatments. The results showed that Valouro-RZ recorded higher vegetative growth and fruit yield compared with Ghandowra-F1 and Feisty-Red cultivars (Table 3). Variations in plant growth and fruit yield parameters between the cultivars could be due to the genetic structure of individual cultivars, as Singh and Singh [45] presented similar results. Mahadeen et al. [18,26] also reported higher WUE values for certain tomato cultivars. In general, tomato farmers can achieve acceptable WUE with the use of moderately saline water; however, crop performance data may vary depending on the cultivar characteristics and salt stress conditions. In the case of the grafted tomato plants, vegetative growth, fruit yield, and WUE were found to be moderately significantly higher compared with the non-grafted plants.

Table 7. Analysis of variation (ANOVA) (mean square) examining agro-morphological traits in tomato plants under different salt stress (S), nutrient (N) recipe, and grafting conditions (season 2).

Parameter	Pr > F				
	Yield	**WUE**	**Plant Height**	**Stem Diameter**	**Leaf Area**
Salinity (S)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Nutrient (N)	0.045	0.045	0.085	0.335	0.333
Grafting (G)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
S*N	<0.0001	<0.0001	0.040	0.031	0.001
S*G	0.158	0.159	0.166	0.507	0.088
N*G	0.706	0.708	0.597	0.264	0.467
S*N*G	0.001	0.001	0.849	0.963	0.036
R^2	0.964	0.961	0.899	0.871	0.892
Coeff. Var.	8.51	8.52	7.41	10.06	9.79
RMSE	1.914	2.248	16.129	1.228	1.392
Mean	23.38	26.44	218.44	12.28	14.23
LSD	1.190	1.332	10.48	0.76	0.84

Table 8. Treatment interaction and response of tomato crops under different salinity and nutrient treatments.

Exp. Treatments		Season 1					Season 2				
		Plant Height (cm)	**Stem Dia. (mm)**	**Leaf Area (m^2 plant $^{-1}$)**	**Yield (t ha^{-1})**	**WUE (kg m^{-3})**	**Plant Height (cm)**	**Stem Dia. (mm)**	**Leaf Area (m^2 $plant^{-1}$)**	**Yield (t ha^{-1})**	**WUE (kg m^{-3})**
S1	GF	203.6 ^{a}	14.8 ^{a}	17.3 ^{a}	291.5 ^{a}	33.5 ^{a}	207.5 ^{a}	14.8 ^{a}	17.3 ^{a}	291.2 ^{a}	31.9 ^{a}
	NG	173.5 ^{bc}	14.6 ^{c}	15.4 ^{c}	237.6 ^{b}	31.2 ^{c}	173.5 ^{b}	13.1 ^{b}	16.1 ^{c}	239.7 ^{b}	32.5 ^{a}
S2	GF	195.6 ^{ab}	14.2 ^{b}	16.6 ^{b}	293.4 ^{a}	32.5 ^{b}	167.8 ^{b}	13.0 ^{b}	16.9 ^{b}	285.5 ^{a}	31.4 ^{b}
	NG	163.8 ^{c}	13.6 ^{cd}	12.9 ^{d}	230.6 ^{b}	24.7 ^{d}	163.8 ^{c}	11.8 ^{c}	13.3 ^{c}	225.1 ^{c}	24.5 ^{c}
S3	GF	138.6 ^{d}	13.4 ^{d}	12.3 ^{e}	170.7 ^{c}	19.4 ^{e}	146.3 ^{d}	11.3 ^{c}	12.5 ^{e}	173.1 ^{d}	19.8 ^{d}
	NG	109.7 ^{e}	12.9 ^{e}	9.5 ^{f}	130.2 ^{d}	14.7 ^{f}	109.7 ^{e}	8.9 ^{d}	9.9 ^{f}	125.6 ^{e}	14.2 ^{e}
S1	N1	210.6 ^{a}	14.6 ^{a}	16.8 ^{ab}	299.3 ^{a}	34.7 ^{a}	196.1 ^{a}	16.2 ^{a}	16.4 ^{bc}	314.9 ^{a}	34.9 ^{a}
	N2	174.8 ^{bcd}	14.9 ^{a}	17.0 ^{a}	255.4 ^{cd}	33.1 ^{b}	223.4 ^{a}	15.5 ^{a}	18.3 ^{a}	259.7 ^{cd}	32.0 ^{b}
	N3	176.9 ^{cde}	14.7 ^{a}	15.5 ^{cd}	247.4 ^{de}	31.8 ^{c}	179.3 ^{b}	13.2 ^{bc}	15.4 ^{d}	240.6 ^{ef}	30.9 ^{c}
	N4	191.9 ^{ab}	13.0 ^{a}	16.1 ^{bc}	256.0 ^{cb}	32.5 ^{bc}	195.8 ^{a}	13.8 ^{b}	16.8 ^{b}	246.7 ^{e}	31.2 ^{bc}
S2	N1	170.7 ^{de}	14.6 ^{a}	14.9 ^{d}	266.4 ^{c}	28.6 ^{d}	172.7 ^{b}	12.1 ^{c}	16.0 ^{cd}	267.8 ^{bc}	29.1 ^{d}
	N2	197.2 ^{abc}	14.8 ^{a}	15.4 ^{cd}	282.6 ^{b}	28.5 ^{d}	172.4 ^{a}	12.7 ^{bc}	15.4 ^{d}	276.7 ^{b}	29.3 ^{d}
	N3	188.9 ^{bcd}	14.7 ^{a}	15.3 ^{cd}	265.7 ^{c}	28.1 ^{d}	157.6 ^{c}	12.6 ^{c}	15.2 ^{d}	251.3 ^{de}	27.3 ^{e}
	N4	162.0 ^{e}	11.3 ^{a}	13.5 ^{e}	233.6 ^{e}	26.6 ^{e}	164.7 ^{c}	12.3 ^{c}	13.8 ^{e}	225.4 ^{f}	26.0 ^{f}
S3	N1	137.7 ^{f}	13.9 ^{a}	11.4 ^{f}	155.7 ^{f}	17.7 ^{f}	139.9 ^{cd}	10.5 ^{d}	11.6 ^{f}	154.2 ^{g}	17.5 ^{g}
	N2	126.2 ^{fg}	13.7 ^{a}	11.2 ^{fg}	152.8 ^{f}	17.3 ^{f}	132.4 ^{d}	10.3 ^{de}	11.4 ^{f}	151.4 ^{g}	17.2 ^{gh}
	N3	115.4 ^{g}	13.6 ^{a}	11.6 ^{fg}	148.9 ^{f}	17.1 ^{fg}	123.0 ^{d}	9.7 ^{e}	11.0 ^{f}	147.2 ^{g}	17.0 ^{gh}
	N4	117.2 ^{g}	10.4 ^{a}	10.5 ^{g}	144.5 ^{f}	16.4 ^{g}	123.3 ^{d}	9.8 ^{de}	10.9 ^{f}	144.6 ^{g}	16.4 ^{h}
GF	N1	188.2 ^{a}	14.6 ^{ab}	15.8 ^{a}	269.1 ^{a}	28.9 ^{a}	172.9 ^{a}	14.1 ^{a}	15.6 ^{b}	270.0 ^{a}	29.5 ^{a}
	N2	180.1 ^{ab}	15.2 ^{a}	16.1 ^{a}	254.5 ^{b}	27.9 ^{b}	179.5 ^{a}	13.7 ^{a}	16.4 ^{a}	256.1 ^{b}	28.1 ^{b}
	N3	174.7 ^{b}	14.4 ^{ab}	14.9 ^{b}	247.2 ^{b}	27.3 ^{bc}	158.8 ^{c}	12.8 ^{b}	15.3 ^{b}	240.0 ^{c}	26.8 ^{c}
	N4	174.0 ^{b}	11.7 ^{b}	14.8 ^{b}	236.8 ^{c}	26.9 ^{c}	178.8 ^{ab}	13.5 ^{a}	15.1 ^{b}	233.6 ^{c}	26.4 ^{c}
NG	N1	157.8 ^{c}	14.6 ^{c}	13.0 ^{c}	211.8 ^{d}	25.1 ^{d}	159.7 ^{c}	11.7 ^{c}	13.7 ^{c}	221.3 ^{d}	24.9 ^{d}
	N2	152.0 ^{cd}	14.4 ^{cd}	12.9 ^{c}	206.1 ^{d}	24.8 ^{d}	172.6 ^{bc}	12.0 ^{c}	13.6 ^{c}	202.4 ^{e}	24.2 ^{d}
	N3	146.1 ^{de}	14.0 ^{de}	12.7 ^{c}	194.2 ^{e}	24.0 ^{e}	147.8 ^{d}	10.9 ^{d}	12.6 ^{d}	186.1 ^{f}	23.3 ^{e}
	N4	140.0 ^{e}	11.6 ^{e}	11.9 ^{d}	185.9 ^{f}	23.4 ^{e}	144.8 ^{d}	10.4 ^{d}	12.4 ^{d}	177.5 ^{g}	22.7 ^{e}

Note: The values with different superscript letters in a column are significantly different ($p < 0.05$).

The grafted plants performed well, and the obtained results are consistent with the study by Di Gioia et al. [46], who reported an increase in the leaf area of greenhouse heirloom tomato Cuore di Bue grafted onto Beaufort and Maxifort rootstocks. The results of the tomato plants grafted onto Maxifort rootstock showed 28.6% and 30.2% higher fruit yield than the non-grafted plants for the first and second seasons, respectively. In another study, Djidonou et al. [47] reported that grafting a tomato cultivar resulted in significantly higher yields and WUE of about 28% greater than non-grafted plants. The results of this study showed that the WUE of the tested tomato cultivars was in the range of 33–52 kg m^{-3} with respect to the salinity treatments, while an overall WUE value of 36–47 kg m^{-3} was obtained with respect to the nutrient treatments.

Low-salinity environments ease the uptake of irrigated nutrient solutions, which can enhance the vigor of vegetative parts and tomato fruit yields [16–18]. In general, salinity stress induces a reduction in the uptake of nutrients, resulting in a low fruit yield. In this study, it was also observed that there was a significant reduction (32.6–39.2%) in total fruit yield in the plants treated with high salinity (i.e., S3) compared with the plants treated with low salinity (S1). This could be due to the reduction in vegetative growth and flower development under high-salinity stress conditions [28,29]. In the present study, concentrations of Na^+, Ca^{2+}, and K^+ decreased in leaf tissues with increasing salinity stress, and this led to lower availability of nutrient solution to the plants (Table 5). These results are in line with those reported by Nahar and Gretzmacher [48], who reported a trend of decreasing concentrations of several minerals, such as Na^+, Ca^{2+}, and K^+, in tomato leaf tissues with increasing water stress, due to high salinity. In general, salinity stress leads to a decrease not only in nutrient uptake by the plant's root system, but also in nutrient transfer from roots to shoots. This is the result of factors such as limited transpiration rate, decreased active transport, and decreased membrane permeability [24,25]. When plants are exposed to high salt concentrations, this causes a water deficit in the plants, which is detrimental to growth. As a result of the increased accumulation of Cl^- and N^+, plants start to experience phytotoxicity and are prevented from absorbing certain nutrients, which leads to nutritional imbalances [8,9]. These elements have an adverse effect on the physiological and metabolic functions of plants, including cell division, respiration, and photosynthesis [10–13], all of which lead to a decrease in vegetative growth and crop yield.

In previous studies, the decrease in tomato yield under high EC was attributed to smaller fruit weight and lower number [48,49]. Another problem often seen in tomatoes grown under high EC is the increased incidence of blossom-end rot (BER) caused by decreased calcium (Ca^{2+}) uptake by roots and increased resistance to xylem transport inside the fruit. However, increasing levels Ca^{2+} in the nutrient solution reduced the incidence of BER [50]. Dorais et al. [49] reported that tomato yields under salinity conditions of 4.6, 8.0, and 12.0 dS m^{-1} were lower compared with those under 2.3 dS m^{-1}. Fruit yields under salinity conditions of 4.6 and 8.0 dS m^{-1} were reduced because of fruit weight, whereas under 12.0 dS m^{-1}, both fruit number and weight were reduced by 5.1% per dS m^{-1} above 2 dS m^{-1} [51].

The levels of chlorophyll, Ca^{2+}, and K^+ concentrations in the leaves of the Feisty-Red cultivar were significantly higher compared with the Valouro-RZ cultivar. However, the concentration of Na^+ was higher in Feisty-Red leaves, although it was not significantly different when compared with other cultivars (Table 9). These results are in line with those reported by Nahar and Gretzmacher [48], who reported significant and insignificant differences between three tested tomato cultivars in terms of K^+ and Na^+ concentrations, respectively. The plants grafted onto Maxifort rootstock showed significantly higher levels of chlorophyll content in their leaves compared with the non-grafted plants. Furthermore, the grafted plants showed lower Ca^{2+} and K^+ concentrations in their leaves than the non-grafted plants (Table 5). This might be due to the higher rate of absorption of water and minerals from the nutrient solution via the roots of the Maxifort rootstock, which could improve the uptake of Ca^{2+} and K^+ [42]. On the other hand, the tomato plants grafted onto the rootstock showed higher Na^+ uptake than the non-grafted plants. These findings suggest that rootstocks can modulate Na^+ accumulation and partitioning within plant shoots [43]. In this study, the leaf tissues of Valouro-RZ plants under the low-salinity conditions (S1) showed the lowest concentrations of Ca^{2+} and K^+. The plants treated with the N2 solution showed the highest Na^+, Ca^{2+}, and K^+ concentrations. However, insignificant differences were observed in Na+ concentration between the tomato cultivars under low- and moderate-salinity conditions. Variations in these mineral concentrations indicated that the strength of uptake of Ca^{2+} and K^+ under the S1N1 treatment and the strength of uptake of Na^+ under the S2N2 treatment were comparable in Valouro-RZ tomato plants. These results are in agreement with Semiz and Suarz [52], who reported that salt resistance of tomato plants grafted onto Maxifort rootstock was due to improved osmoregulation, which was partially induced by the higher proline and relative water contents in tomato scions.

Table 9. Leaf tissue analysis of interaction of salinity and nutrient recipe treatments with respect to chlorophyll and ion concentrations in tomato plants.

Source		Season 1				Season 2			
		Chlorophyll	**Ca^{2+}**	**K^+**	**Na^+**	**Chlorophyll**	**Ca^{2+}**	**K^+**	**Na^+**
Pr > F	Salinity (S)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Nutrient (N)	<0.0001	0.0336	0.0014	0.0008	<0.0001	0.0394	0.0141	0.0008
	Graft (G)	0.36063	0.71442	0.79227	0.77292	0.3446	0.6826	0.757	0.7385
	S*N	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0394	0.0141	0.0008
	S*G	0.10926	0.43533	0.26676	0.2817	0.1044	0.4159	0.2549	0.2692
	N*G	0.00009	0.00729	0.00333	0.00279	0.0008	0.0069	0.0031	0.0027
	S*N*G	0.17847	0.33777	0.459	0.38961	0.1705	0.3227	0.4386	0.3722
$LSD_{0.05}$		0.00252	0.01476	0.0105	0.00918	0.0028	0.0164	0.0117	0.0102

Principal Component Analysis

Principal component analysis (PCA) was performed to identify the main parameters of the studied agro-morphological traits that could be used to evaluate and select the most appropriate salinity level, nutrient, and grafting conditions (Figure 3). The first three principal components (F1, F2, and F3) explained 94.31% of the phenotypic variation and covered all measured traits (Table 10). The first two principal components (F1 and F2) had eigenvalues greater than 7.5 and explained 68.56% and 13.2% of the total variance, respectively. Salinity had a score of >0.73 and loaded positively onto PC1, while the other measured traits of plant height, stem diameter, leaf area, fruit yield, and WUE had high scores > 0.88 (Table 10). PC1 had a positive correlation with all measured traits except for nutrient and grafting treatments, which demonstrated a negative correlation with all other traits. The eigenvector's distance and direction characterized the relationships between the traits and the imposed treatments. The scattering of the studied tomato traits in the same direction helped group them by similar physiological traits that were associated with salt tolerance. The PCA demonstrated that WUE had a stronger correlation with salinity treatment than with other parameters, followed by grafting status.

Table 10. Principal component analysis of tomato traits: eigenvalues, proportion, and cumulative variance for the four principal components underlying the effects of salinity stress.

	F1	**F2**	**F3**	**F4**
Eigenvalue	5.485	1.056	1.004	0.199
Variability (%)	68.562	13.201	12.555	2.493
Cumulative %	68.562	81.763	94.318	96.810
Salinity	**0.726**	0.219	0.007	0.001
Nutrient	0.029	0.025	**0.943**	0.000
Grafting	0.183	**0.751**	0.049	0.003
Plant height	**0.925**	0.001	0.000	0.035
Stem diameter	**0.885**	0.018	0.001	0.082
Leaf area	**0.926**	0.003	0.001	0.017
Yield	**0.909**	0.002	0.003	0.018
WUE	**0.901**	0.037	0.000	0.044

Note: Values $\geq$ 0.48 are presented in boldface and indicate traits found to be important for salinity tolerance.

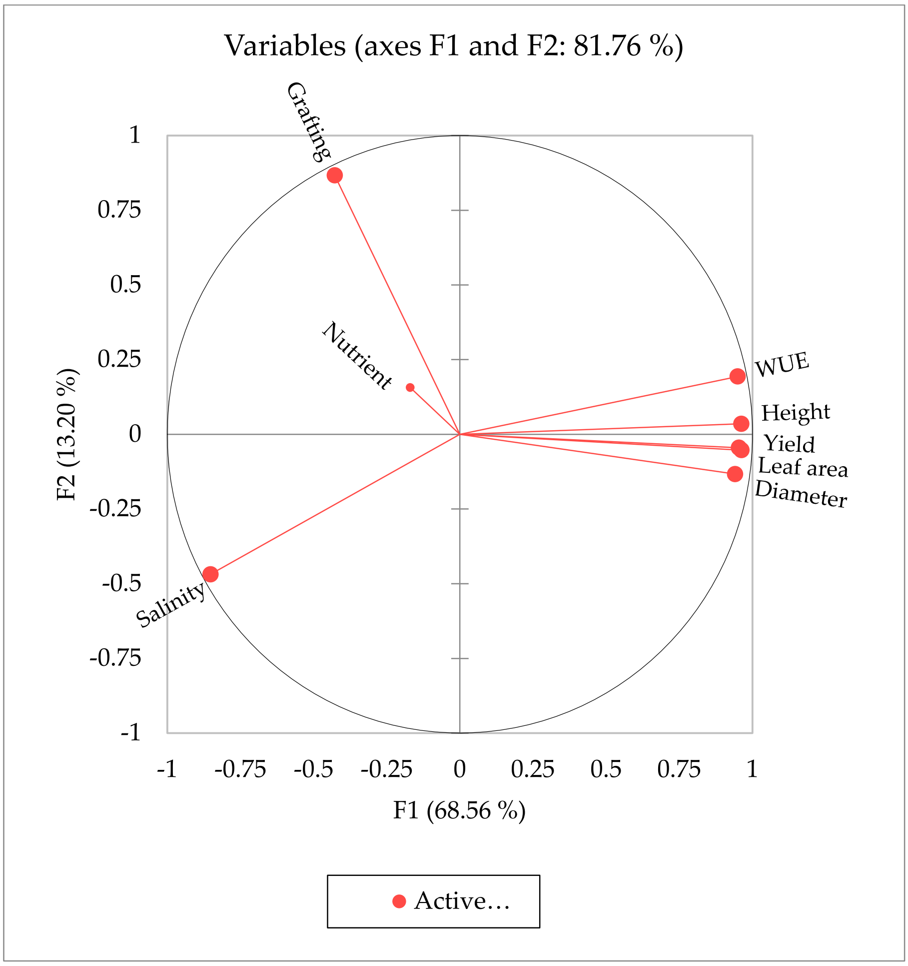


Figure 3. Principal component analysis (PCA) results: factor (F) and water use efficiency (WUE).

5. Conclusions

An adverse effect of high salinity stress (~9 dS m^{-1}) was evident in non-grafted plants, especially in the Valouro-RZ cultivar. A positive effect of grafting was observed when Maxifort was used as a rootstock. A modified nutrient solution [N2] was found to have a significant impact when used in combination with moderate salinity level (~6.0 dS m^{-1}), as it exhibited a high mean yield (24 kg m^{-2}), with a reduction of about ~20% in yield when compared with the control (i.e., combination of S1 and N1). High saline water significantly affected WUE, whose value was the highest at 34.7 kg m^{-3} for the control (S1 and N1), followed by the S2 (28.0 kg m^{-3}) and S3 conditions (17.5 kg m^{-3}). These results revealed that the studied tomato cultivars could be grown successfully under a hydroponic system using irrigation water with up to 6.0 dS m^{-1} salt concentration in combination with the N2 recipe without affecting total fruit yield. The results also indicated that grafting could mitigate some of the negative effects of salinity stress on tomato plants grown under hydroponic conditions.

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