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Article

The Use of Spectral Vegetation Indices to Evaluate the Effect of Grafting and Salt Concentration on the Growth Performance of Different Tomato Varieties Grown Hydroponically

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Abstract: Water scarcity has prompted researchers to intensify studies on the optimal use of saline water in irrigating agricultural crops to improve the efficiency of exploiting available water resources. Therefore, this study aimed to use selected spectral vegetation indices to investigate the potential of grafting in mitigating the effect of salinity on the growth of tomato plants grown under a hydroponic system. Three commercial tomato cultivars (Forester-F1, Feisty-Red, and Ghandowra-F1,) and five tomato hybrid rootstocks (Beaufort, Maxifort, Dynafort, Unifort, and Vivifort) were investigated using nutrient solutions at three salinity levels, namely, 2.5 dS m^{-1} (S1, low salinity level), 6.0 dS m^{-1} (S2, medium salinity level), and 9.5 dS m^{-1} (S3, high salinity level). The results showed that Ghandowra-F1 had the best growth performance under hydroponics compared to the other two varieties. The increase in the salinity of the nutrient solution negatively affected the vegetation growth of tomato plants. Low and medium salinity did not show any significant effect on the three tomato varieties, unlike high salinity, which showed a significant negative effect on the vegetative growth of the plant. Thus, it is possible to successfully grow tomatoes in hydroponics using nutrient solutions with a salt concentration of up to 6.0 dS m^{-1}. Although there was a slight improvement in the vegetative growth of grafted tomato plants, all the studied rootstocks showed no significant differences compared to non-grafted tomato plants. This study could greatly contribute to strategies targeting the improvement of tomato production in hydroponics.

Keywords: hydroponics; spectroscopy; vegetation indices; tomato; grafting

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1. Introduction

Water scarcity and salinity are among the most important environmental factors that limit the expansion of agricultural production in arid and semi-arid regions such as Saudi Arabia. This has prompted researchers to intensify studies on the use of saline water in irrigation to increase the efficiency of using available water resources, as well as recycling wastewater, developing crops that tolerate high salinity, and adopting effective water management strategies. Furthermore, grafting plants onto rootstocks that are able to resist the effects of salinity on plant growth and health is also an effective way to reduce production losses due to salinity.

Environmentally controlled agricultural systems provide crop protection against the direct influence of external weather conditions, as well as the opportunity to modify the internal climate to create an ideal environment for crop growth and production [1]. These systems, which are also known as indoor farming, have the advantage over conventional farming methods of largely separating production processes from the natural environment and better restricting and controlling pollution, while the production potential of conventional agriculture is suffering globally due to the effects of climate change [2]. Similarly, Wang et al. [3] reported that the clear advantages of controlled environmental agriculture over conventional agriculture include its ability to produce reliably and consistently, its efficient water and space use, and its optimized use of fertilizers and pesticides. Hydroponics, a soilless farming system, is gaining increasing attention because it reduces dependence on agricultural land and pesticides and can be implemented in areas with poor soil quality, thus mitigating the negative effects of extreme weather conditions [4]. Hydroponic systems are among the most important modern technologies that ensure the production of high-quality vegetables throughout the year in greenhouses developed to operate under controlled weather conditions. Hydroponics has many advantages over traditional agricultural techniques, such as soil and greenhouses, because it allows for optimal use of water, reducing water use by about 90% compared to traditional agricultural methods [5]. In addition, hydroponics, when using carefully calibrated nutrient solutions, can produce much larger quantities of vegetables than traditional soil farming, as it allows for a greater yield per unit area due to the vertical farming characteristics that promote the efficient use of available space [6].

Tomato (*Solanum lycopersicum* L.) is one of the most important economically produced vegetables around the world in open fields and greenhouses using soil and soilless techniques. However, most tomato cultivars are moderately susceptible to salt stress, which affects seed germination and the vegetative and reproductive stages of growth salinity, causing considerable reductions in tomato growth and yield [7]. The grafting of horticultural crops is an effective technique to obtain a composite plant capable of maintaining an appropriate growth pattern and mitigating the effect of unfavorable environments such as biotic and abiotic stresses caused by low and high temperatures and water stress conditions without a loss in yield [8–10]. The use of salt-tolerant stocks is an effective strategy to mitigate the negative effects of salinity on tomatoes with the aim of improving plant strength and enhancing nutrient and water absorption efficiency, as well as fruit quality and formation [11,12]. Wu et al. [13] also reported that grafting tomatoes onto salt-tolerant rootstocks aids in various metabolic processes and transcriptional changes in scion leaves, which gives the scion leaves greater salt tolerance. In addition, previous studies showed that grafting tomato plants improves the nitrogen efficiency mechanism and thus increases the yield and productivity of the crop and improves the quality of the fruits compared to non-grafted tomatoes [14,15].

The biochemical and physiological methods used to assess plant stress are expensive, invasive, and time-consuming. Therefore, spectroscopic analysis has become an effective alternative for monitoring the biochemical components and physiological states of plants. In this regard, the ability of spectroscopy to monitor salt stress in tomato plants, in a non-destructive manner, could serve as a basis for developing a low-cost, rapid, and effective method for stress detection, regardless of environmental conditions [16]. Furthermore, the use of modern technologies such as field spectroscopy, which provides multispectral data, can add valuable insights to sustainable agriculture by improving effective tools for monitoring agricultural crops. Therefore, the main objective of this study was to employ selected spectral vegetation indices to investigate the potential of grafting rootstocks in mitigating the effect of salinity on plant growth for selected commercial tomato varieties under a hydroponic system. The specific objectives are

(i) To determine selected vegetation indices as key parameters for evaluating the effect of grafting and salinity levels on the growth performance of selected commercial tomato varieties grown hydroponically,
(ii) To study the response of tomato plant growth performance to the variety, grafting rootstock, and salt concentration, and their interactive effects.

2. Materials and Methods

2.1. Experimental Layout

The experiments were conducted in the hydroponic greenhouse of the Precision Agriculture Research Chair (PARC) located in the Educational Farm of the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia. Riyadh, the capital of Saudi Arabia, is located in an arid climate at an elevation of approximately 700 m meters above sea level, with average air temperatures ranging from 15 °C in winter to 35.5 °C in summer. Spring is the wettest season, with an average rainfall of 22.4 mm, while summer is the driest season, with an average rainfall of less than 1.0 mm [17]. Experimental work was carried out during the growing season of tomato plants grown in the period from the last week of September 2022 to the first week of April 2023. The hydroponic system consists of twelve 28 m long planting troughs, laid with 1000 mm × 250 mm × 200 mm perlite bags. The nutrient solution was supplied to plants using a separate electric pump for each planting line, and the flow of the nutrient solution was automated with a continuous daily supply. The electrical conductivity (EC) and pH of the nutrient solution were automatically regulated to target values and monitored by sensors.

Three commercial varieties of tomato plants (Feisty-Red, Ghandowra-F1, and Forester-F1) were investigated in this study. Five tomato hybrid rootstocks (Maxifort, Unifort, Dynafort, Vivifort, and Beaufort) were selected for grafting the selected tomato varieties, using the tube grafting technique. Seedlings of non-grafted and grafted tomato plants were transplanted 45 days after sowing using perlite as a growing medium, with a plant spacing of 250 mm in the planting line (row) and 1750 mm between rows. The experiments were conducted using nutrient solutions with three salinity levels, namely low salinity (S1, 2.5 dS m^{-1}), medium salinity, (S2, 6.0 dS m^{-1}), and high salinity (S3, 9.5 dS m^{-1}). The nutrient solution was adjusted during the growing season to have a pH value in the range between 5.5 and 6.5. Salinity levels were prepared by adding different amounts of sodium chloride (NaCl) to the irrigation water, taking into account the salt concentration in the irrigation water and nutrient solution. Tomato plants were supplied with the nutrient solution (Table 1), as recommended by Hochmuth and Hochmuth [18], for different plant growth stages, through a drip fertigation system using simple drippers with a flow rate of 3 L/h/emitter.

Table 1. Detailed formulation of the nutrient solution [18].

Nutrient (ppm)	Transplant to 1st Cluster	1st to 2nd Cluster	2nd to 3rd Cluster	3rd to 5th Cluster	5th 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

Table 1. *Cont.*

Nutrient (ppm)	Transplant to 1st Cluster	1st to 2nd Cluster	2nd to 3rd Cluster	3rd to 5th Cluster	5th Cluster to Termination
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

2.2. Spectral Data Collection

Spectral reflectance measurements of tomato plants were collected in the laboratory using a FieldSpec3 spectroradiometer (Analytical Spectral Devices Inc., Longmont, CO, USA) and a direct-contact probe method in a wavelength range of 350–2500 nm. Spectral reflectance data were recorded 65 days after transplanting (DAT)—i.e., the flowering stage—from three young, fully developed leaves from three randomly selected plants in each of the three replicates. The three collected spectra were then averaged to produce a single spectral reflectance for each replicate.

2.3. Spectral Vegetation Indices

Among more than thirty vegetation indices examined in this study, the four most informative indices were selected to investigate the growth response of tomato plant to different varieties, salinity levels, and grafting rootstocks. The four selected vegetation indices are as follows:

Moisture Stress Index (MSI): This is a sensitive reflection measure of increases in leaf water content, with higher values indicate lower water content and therefore higher water stress [19]. It is calculated according to Equation (1) [20].

$$\text{Moisture Stress Index, MSI} = \frac{R_{1600}}{R_{820}} \tag{1}$$

where R1600 and R820 are the reflectance values at 1600 and 820 nm wavelengths.

Normalized Difference Infrared Index (NDII): This is a powerful and effective indicator for monitoring water content in vegetation and assessing drought conditions, with values increasing with increasing water content; it is calculated as the ratio between the near-infrared (NIR) and short-wave infrared (SWIR) bands according to Equation (2) [21,22].

$$\text{Normaized Difference Infrared Index, NDII} = \frac{R_{850} - R_{1650}}{R_{850} + R_{1650}} \tag{2}$$

where R1600 and R820 are the reflectance values at 1600 and 820 nm wavelengths.

Carotenoid Reflectance Indices 1 and 2 (CRI1 and CRI2): CRI1 is a sensitive reflectance measure of carotenoid pigments in plant leaves, calculated using Equation (3). Meanwhile, CRI2 is a modification of CRI1 and provides better results in areas with a high carotenoid concentration. CRI2 is calculated using Equation (4). Higher values of CRI1 and CRI2 mean higher carotenoid concentrations relative to chlorophyll. Changes in the carotenoid content of leaves are widely used to diagnose the physiological status of plants during growth, acclimatization, and adaptation to different environmental conditions and stresses [23]. The decrease in the rate of photosynthesis, due to plant stress, resulted in high concentrations of carotenoid and anthocyanin pigments relative to those of chlorophyll [24].

$$\text{Carotenoid Reflectance Index, CRI1} = \frac{1}{R_{510}} - \frac{1}{R_{550}} \tag{3}$$

$$\text{Carotenoid Reflectance Index, CRI2} = \frac{1}{R_{510}} - \frac{1}{R_{700}} \quad (4)$$

where R510, R550, and R700 are the reflectance values at 510, 550, and 700 nm wavelengths.

2.4. Statistical Analysis

A three-factor experiment with a completely randomized block design was adopted for this study, with three varieties, three salinity levels, and six grafting treatments as the experimental variables. The collected data were subjected to an analysis of variance using the Statitix 10 software, and the mean values were compared for significance using the least significant difference at a confident level of 0.05 ($LSD_{0.05}$).

3. Results and Discussion

3.1. The Response of Vegetation Growth to Tomato Variety, Salinity Level, and Grafting Rootstock

The results presented in Figure 1 indicate that the vegetation growth of tomato plants, represented by selected vegetation indices, showed significant responses to varieties, salinity levels, and grafting rootstocks. The comparison results between the studied varieties have proven the superiority of Ghandowra-F1 to the other varieties, as indicated by the lowest average value of the Moisture Stress Index (MSI: 0.5673) and the highest average value of the Normalized Difference Infrared Index (NDII: 0.2370). High MSI values indicate greater water stress [19], and high NDII values indicate high water content and hence low water stress [22]. Furthermore, the statistical analysis results showed large significant differences between Ghandowra-F1 and both the Forster-F1 and Feisty-Red varieties in terms of the values of the MSI ($Pr > F = 0.0016$) and NDII ($Pr > F = 0.0006$). Overall, Ghandowra-F1 showed the best growth performance under hydroponics compared to the other two tomato varieties.

The results also showed the significant negative impact of salinity on the vegetation growth of tomato plants; this was reflected in the increase in the average MSI values with the increase in salt concentrations. The highest average MSI value (0.6174) was recorded at salinity-3, with significant differences from that recorded at both salinity-1 (0.5524) and salinity-2 (0.5638). The impact of salinity on the growth performance of tomato plants has also been confirmed by the lowest average values of the NDII (0.1959), CRI1 (6.0669), and CRI2 (5.2716) at salinity-3, with significant differences compared to those at salinity-1 (NDII—0.2507, CRI1—6.3269 and CRI2—5.5462). These results are in line with those reported by Hajer et al. [25] that salt stress significantly stunted tomato plant growth, with increased salinity accompanied by significant reductions in shoot weight, plant height, and root length. Zhang et al. [26] reported, in the same context, that under most environmental conditions and tomato varieties, tomato growth inhibition and yield loss began when the EC of the nutrient solution was higher than 2.5 dS m^{-1}.

Although the grafting rootstocks showed no significant improvement in the vegetation growth of the hydroponic tomato plant, the best results for the vegetation indices were recorded for the Beaufort rootstock. The average values of the studied vegetation indices for the Beaufort-grafted tomato plants were 0.5699 (MSI), 0.2355 (NDII), 6.1852 (CRI1), and 5.4819 (CRI2) compared to those recorded for the non-grafted (control) plants, which amounted to 0.5677 (MSI), 0.2364 (NDII), 6.1471 (CRI1), and 5.4673 (CRI2). These results agree with those of Di Giota et al. [27], who found that at higher salinity stress levels (40 mm of NaCl, i.e., 4.0 dS m^{-1}), tomato grafting did not enhance the crop salinity tolerance, as the fruit's total soluble solid content, titratable acidity, and dry matter were unaffected by grafting at any salinity stress level. In contrast, Dudhat et al. [28] reported that grafting treatments increased the values of all recorded tomato vegetative growth and productivity traits over non-grafted plants under all salinity levels. Similarly, Martinez-Rodriguez et al. [29]

reported that the grafting of tomato improved the fruit yield compared to non-grafted plants grown at 50 mM NaCl (5.0 dS m^{-1}), while there was no effect of either grafting rootstocks on fruit yield at 25 mM NaCl (2.5 dS m^{-1}). In addition, Soare et al. [30] indicated that grafting tomato plants had a significant effect on vegetative growth, while fruit quality was not improved in any of the grafted tomato varieties.

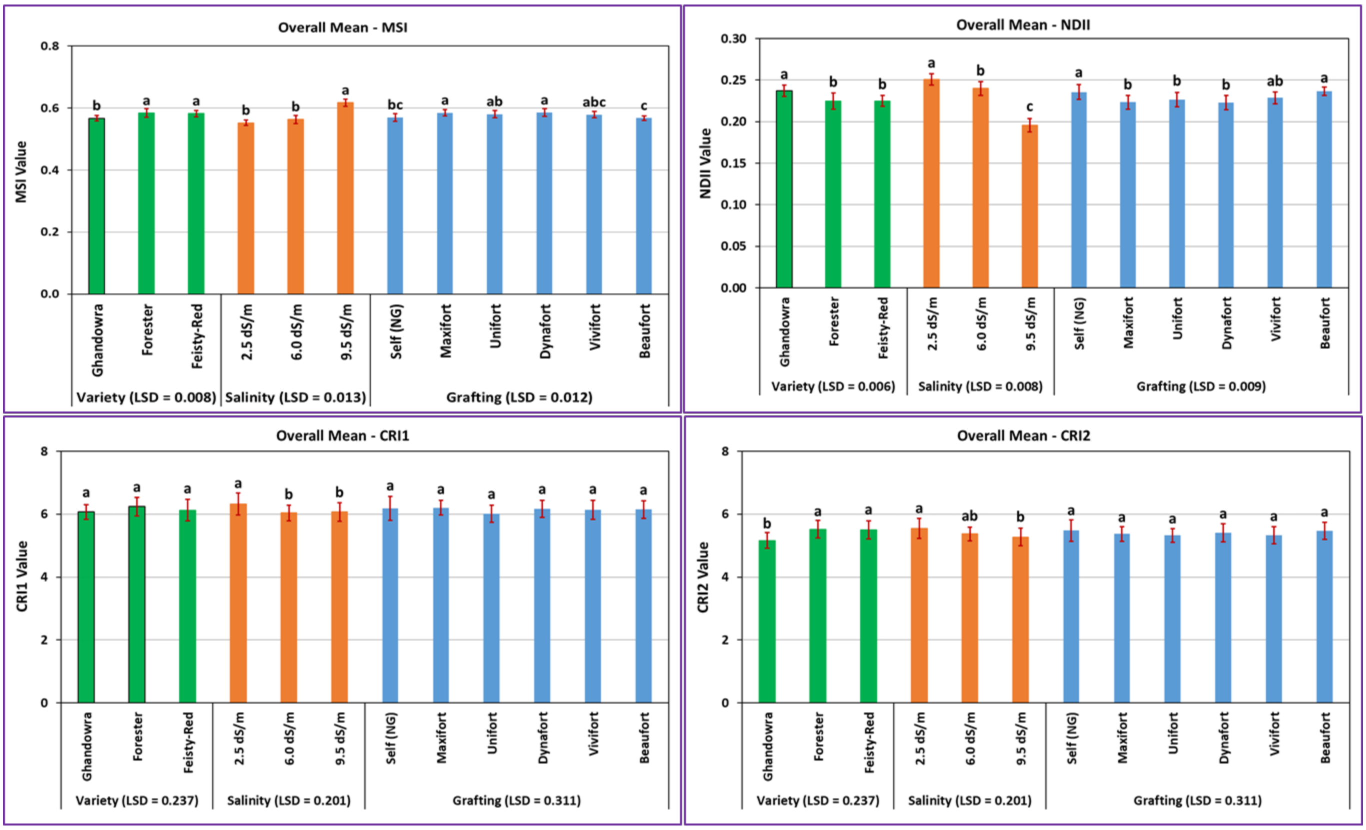

Figure 1. Mean values of vegetation indices (VIs) corresponding to tomato varieties, salinity levels, and grafting rootstocks. VIs: MSI (Moisture Stress Index); NDII (Normalized Difference Infrared Index); CRI1 (Carotenoid Reflectance Index (1); CRI2 (Carotenoid Reflectance Index (2). Columns with different letters showed significant differences ($LSD_{0.05}$).

3.2. The Response of the Vegetative Growth of Tomato Plant to the Interactive Effect of Variety and Salinity

The interactive impact of variety and salinity on the vegetative growth of tomato plants in terms of VIs is shown in Figure 2. Both the MSI and NDII results showed that the highest moisture stress for the three varieties was associated with the highest salinity level (S3). The Ghandowra-F1 variety was found to be more tolerant to high salinity, as indicated by it having the lowest MSI value (0.5819), with significant differences compared to that for both the Forester-F1 (0.6412) and Feisty-Red (0.6291) varieties. The same results were obtained for the NDII, where the Ghandowra-F1 variety showed the highest NDII value (0.2235) with significant differences compared to the Forester-F1 (0.1777) and Feisty-Red (0.1865) varieties. Furthermore, the superiority of the Ghandowra-F1 variety under a high salinity level was confirmed by the lowest CRI2 value (4.93), with significant differences compared to that for the Forester-F1 (5.53) and Feisty-Red (5.36) varieties. Although low salinity (S1; 2.5 dS m^{-1}) and medium salinity (S2; 6.0 dS m^{-1}) showed no significant impact on the three tomato varieties, high salinity (S3; 9.5 dS m^{-1}) resulted in a significantly negative impact on the vegetative growth of the three varieties, where the Ghandowra-F1 variety showed the best vegetative growth under salinity stress. These results are consistent with those of Zhang et al. [31], who found that the interactive effect of tomato genotypes and salinity indicates that different genotypes have distinct responses to different salinity levels. An abundance of evidence also indicated a large variation in salinity tolerance among different tomato plant species [32].

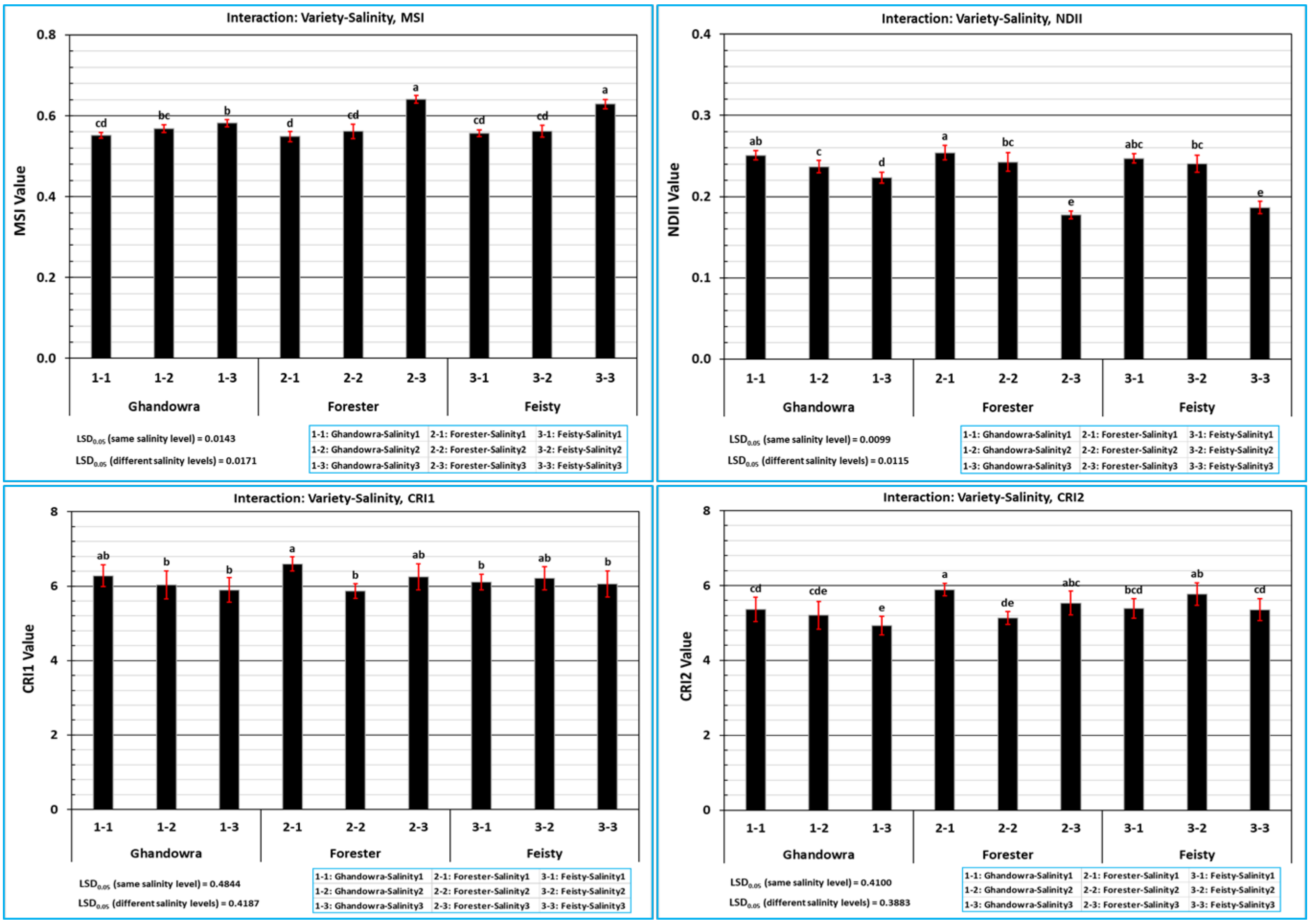

Figure 2. Interactive effect of variety and salinity on the vegetative growth of tomato plants in terms of vegetation indices (VIs). VIs: MSI (Moisture Stress Index); NDII (Normalized Difference Infrared Index); CRI1 (Carotenoid Reflectance Index (1); CRI2 (Carotenoid Reflectance Index (2). Columns with different letters showed significant differences ($LSD_{0.05}$).

3.3. The Response of the Vegetative Growth of Tomato Plant to the Interactive Effect of Variety and Grafting

Although the interactive effect of variety and grafting showed no significant impact on the vegetative growth performance of tomato plant compared to the non-grafted treatments, the Beaufort rootstock showed the best results compared to the other rootstocks, as indicted by it having the lowest MSI and highest NDII, CRI1, and CRI2 values (Figure 3). Similar results were reported by Rajametov et al. [33], who found that the response of tomato varieties to grafting varies according to the effect of the rootstock on vegetative and reproductive traits according to the characteristics of each genotype (scion), and despite this, no significant differences were recorded between the grafted and non-grafted tomato plants.

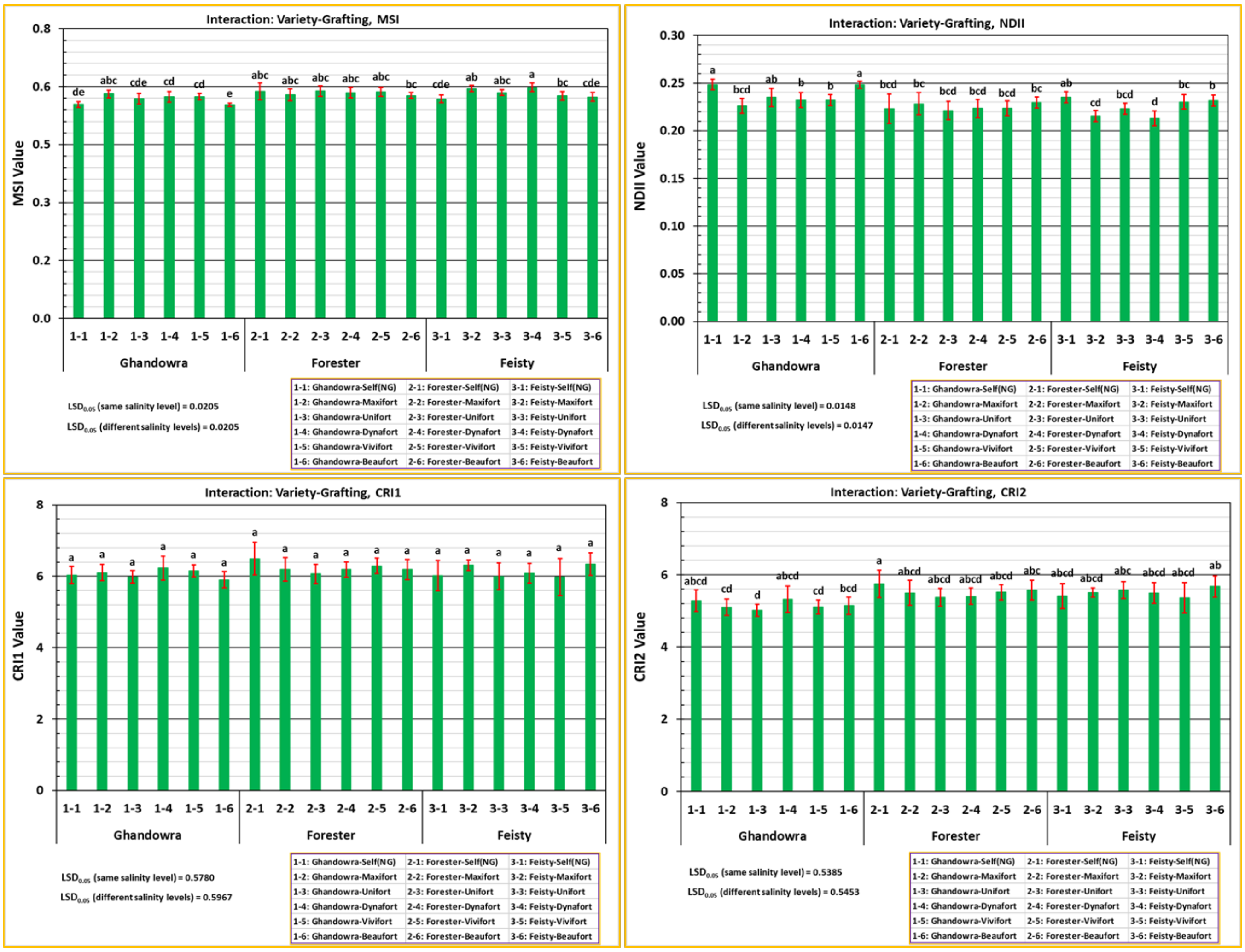

Figure 3. Interactive effect of variety and grafting on the vegetative growth of tomato plants in terms of vegetation indices (VIs). VIs: MSI (Moisture Stress Index); NDII (Normalized Difference Infrared Index); CRI1 (Carotenoid Reflectance Index (1); CRI2 (Carotenoid Reflectance Index (2). Columns with different letters showed significant differences ($LSD_{0.05}$).

3.4. The Response of the Vegetative Growth of Tomato Plants to the Interactive Effect of Salinity and Grafting

The interactive effects of salinity and grafting on the vegetative growth of tomato plants is indicated by the results of the VIs shown in Figure 4. The MSI results showed no significant differences between the grafted and non-grafted plants under all salinities. The NDII results also indicated that the interactive effects of salinity and grafting showed no significant differences, with Beaufort showing the highest values compared to the control and other grafting rootstocks. Semiz et al. [34] reported an increase in yield associated with Big Dena tomatoes grafted onto Maxifort rootstock, both under the control and under different salinity levels compared to non-grafted plants, and the grafted Big Dena plants were less tolerant to salinity than the non-grafted plants. Meanwhile, the results of Wahb-Allah [35] indicated that grafting mitigated the negative effects of water and salt stresses in tomatoes grown under greenhouse conditions.

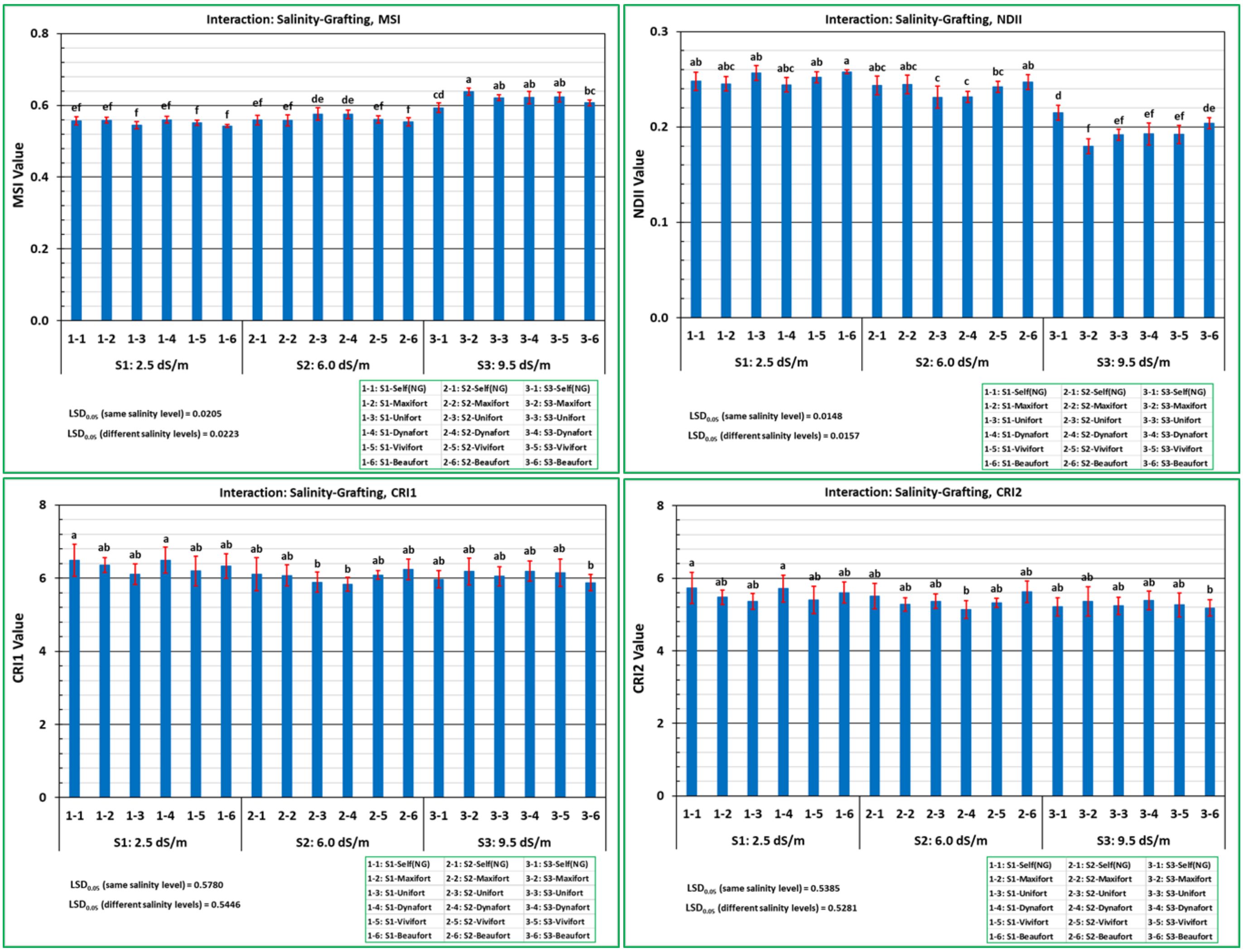

Figure 4. Interactive effect of salinity and grafting on the vegetative growth of tomato plants in terms of vegetation indices (VIs). VIs: MSI (Moisture Stress Index); NDII (Normalized Difference Infrared Index); CRI1 (Carotenoid Reflectance Index (1); CRI2 (Carotenoid Reflectance Index (2). Columns with different letters showed significant differences ($LSD_{0.05}$).

4. Conclusions

The studied tomato varieties showed different responses to salinity and grafting, where Ghandowra-F1 showed the best growth performance under hydroponics compared to the other two varieties. The increase in the salinity of the nutrient solution negatively affected the vegetation growth of tomato plants. However, both low salinity (S1, 2.5 dS m^{-1}) and medium salinity (S2, 6.0 dS m^{-1}) showed no significant effect on the three tomato varieties. On the other hand, high salinity (S3, 9.5 dS m^{-1}) had a significant negative effect on the vegetative growth of the three varieties. Thus, tomatoes can be successfully grown under hydroponics using nutrient solutions with a salt concentration of up to 6.0 dS m^{-1}. However, the studied grafting rootstocks showed no significant improvement in terms of the vegetative growth of tomato plants.

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

Abbreviations

The following abbreviations are used in this manuscript:

S1, S2, S3	Salinity1, Salinity2, Salinity3
VIs	Vegetation Indices
MSI	Moisture Stress Index
NDII	Normalized Difference Infrared Index
CRI1	Carotenoid Reflectance Index 1
CRI2	Carotenoid Reflectance Index 2
DAT	Days After Transplanting
LSD	Least Significant Difference

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