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THE EFFECT OF NaCl-SALINITY APPLICATIONS ON THE IMPROVEMENT OF QUALITY CHARACTERISTICS AND YIELD OF TOMATO (*LYCOPERSICON ESCULENTUM* L.) GROWN IN SUBSTRATE CULTURE

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Abstract: Salt application in soilless cultivation systems can be considered as a strategic tool to improve tomato fruit quality. In this context, the effects of increasing the salt concentration in the nutrient solution added to the solid culture medium on yield and yield components, biophysical and organoleptic quality traits of tomato (*Lycopersicon esculentum* L. cv. Kardelen F1) under greenhouse conditions were studied. The salt in the nutrient solution was applied to tomato plants as sodium chloride (NaCl) at four concentrations (0, 14.1, 44.4, and 70.4 mM). Each pot received 150 mL of nutrient solution daily during the vegetative period, while 300 mL was applied daily after flowering. This study was conducted with three replicates following a randomized block design. Plants were harvested 90 days after transplanting. Low salt application in the nutrient solution (14.1 mM NaCl) increased total fruit yield, while the high salt application did not effect fruit yield compared to the control. Salt application at increasing concentrations decreased fruit size and diameter but increased the dry matter in the fruit. The salt treatment mainly positively affected the commercial and organoleptic quality parameters of the tomato fruits. In conclusion, a low level of sodium chloride (14.1 mM NaCl) in soilless culture enhanced fruit production, while moderate (44.4 mM) and high (70.4 mM) concentrations improved various fruit quality traits.

Keywords: *Lycopersicon Esculentum*, Substrate Culture, NaCl, Yield, Organoleptic and Biophysical Quality

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1. Introduction

Currently, soilless cultivation is gaining popularity as a new type of intensive and efficient technology (Lucke et al., 2019). Soilless cultivation is a method of growing plants that does not use soil as a rooting medium. It is widely used to improve the regulation of environmental conditions for growth and to avoid soil ambiguity (Tzortzakis et al., 2020). The techniques of solid substrate culture can be divided into the hanging bag technique, the grow bag technique, the trench or trough technique and the pot technique. These techniques require solid substrates. The chosen medium must be flexible, friable, water and air retentive and easy to drain. It must also be free of toxic substances, pests, pathogenic microorganisms and nematodes (Fussy and Papenbrock, 2022). The plants are grown in a substrate with a continual supply of nutrient solution, allowing for optimal mineral nutrition management (Lu et al., 2022). Commercially, substrate culture has been used successfully for fruiting vegetables (Tüzel et al., 2019).

Tomato is a popular vegetable grown on large areas around the world and has a high production potential compared to other vegetables (Nangare et al., 2016; Cui et al., 2019). Tomato fruit contains many phytochemical compounds that can improve human health (Talens et al., 2016). This fruit is an important dietary source of lycopene, potassium, iron, folic acid and vitamin C (Alsuhaibani, 2018; Rana et al., 2019; Gonçalves et al., 2020; Wu et al., 2022). In addition, tomatoes provide other antioxidants such as β-carotene and phenolic compounds such as flavonoids (Tomas et al., 2017; Botella et al., 2021; Izzo et al., 2022).

Consumers are becoming more aware of the quality of fruit and vegetables and are demanding higher quality in the products they buy (Mascarello et al., 2015; Petrescu et al., 2019; Alam et al., 2021). The quality of a fresh food product includes characteristics such as colour, texture, taste and health-promoting compounds, but can also include undesirable characteristics such as possible damage or spoilage (Amit et al., 2017; Sajdakowska et al., 2018). Although all these intrinsic attributes are included in the definition of quality, most breeding studies and efforts have been aimed mainly at improving and maintaining external quality for many years. Selection for yield, size, colour, and shelf life can have unintended negative effects on fruit quality (Zhang et al., 2016; Lara et al., 2019; Thole et al., 2020).

Plants are exposed to various stress factors throughout their life cycle (Mareri et al., 2022). Excessive salinity is one of the most critical environmental stressors that drastically affects the growth, nutrition and productivity of many plant species (Shrivastava and Kumar, 2015; Ma et al., 2020). The response of plants to salinity is complex and involves physiological and biochemical processes as well as morphological and developmental changes (Arif et al., 2020). On the other hand, the use of controlled abiotic stress could be an interesting approach to improving the nutraceutical value of fruits and vegetables (Toscano et al., 2019). In addition, increasing the EC of the nutrient solution is used to improve fruit quality when growing tomatoes with soilless cultivation techniques. This is done either; by increasing the amount of fertilizer added to the nutrient solution or by adding sodium chloride (NaCl) salt to the nutrient solution. The second way is preferred because it is cheaper (Gül, 2018). Cultural management provides excellent possibilities to obtain the high nutritional and organoleptic quality of fresh tomato fruits (Bertin and Génard, 2018; Coyago-Cruz et al., 2018; Asensio et al., 2019; Lima et al., 2022). In addition, the nutritional and organoleptic quality of fresh tomatoes can be influenced by many pre- and postharvest factors, such as genetic characteristics, growing conditions, stage of maturity at harvest and crop management (Arah et al., 2015; Iglesias et al., 2015; Urrestarazu et al., 2015; Distefano et al., 2022).

Although there are negative effects, an increase in the total salt concentration in the root zone of tomatoes is a factor that affects fruit quality as well as individual nutrients (Zhang et al., 2016). Increasing root zone salinity in moderate levels improves tomato fruit quality (Krauss et al., 2006). Improvements in fruit quality with salinity have been found to be related to increases in the content of sugars, organic acids, and amino acids in fruit (Rodríguez et al. 2019; Ávalos-Sánchez et al., 2022). Other studies have reported that red fruit colour and shelf life increase with salinity (Sonneveld and Van Der Burg, 1991; Botella et al., 2000). In addition to these, an increase in the total salt concentration in the nutrient solution increased the concentration of vitamin C, lycopene, and β-carotene (Tzortzakis et al., 2022).

The tomato is generally considered a moderately salt-tolerant plant (Ladewig et al., 2021). The maximum yield for tomato plants grown in substrate is achieved at an electrical conductivity value (EC) of 2.5 to 2.9 $dS \cdot m^{-1}$ (Sonneveld and Van Der Burg, 1991). Furthermore, Sonneveld and Straver (1994) reported that salt should be added to the nutrient solution to increase the EC value to 3.5–3.7 $dS \cdot m^{-1}$ for tomato plants.

Most cultivation practices have been used to optimize crop characteristics and yield, but little attention has been paid to the impact on fruit quality (Sánchez-González et al., 2016). Moreover, there is little information on the effects of increased salt concentration in the nutrient solution on plants in soilless cultivation (Moya et al., 2017). In soilless agriculture, elevated EC values in nutrient solutions are generally linked to adverse effects on plant growth and development as a result of increased salinity stress. However, this study highlights the beneficial role of controlled salinity achieved through the application of sodium chloride (NaCl). Therefore, we aimed to investigate the effects of increasing doses of sodium chloride in the nutrient solution on the yield and fruit quality of tomato plants grown in substrate culture.

2. Materials and Methods

Tomato (*Lycopersicon esculentum* L. cv. Kardelen F_1) was used as plant material. Seedlings were produced in a commercial nursery located in Antalya (Turkey).

The tomato seedlings, which were approximately four inches tall and with their second pair of leaves, were planted singly in pots on 07/07/2022. The pots were placed in the greenhouse of Ondokuz Mayıs University in Turkey under controlled conditions with a diurnal temperature of 28/21ºC and a relative humidity of 55 % ± 5 %.

In the experiment, peat and perlite were mixed at the ratio of 2:1 (v/v) for the growth medium. Peat moss (Klasmann) is a moss that belongs to the genus of peat moss (Sphagnum) and has a high water-holding capacity and a pH value between 5.5 and 6.0. The expanded mineral perlite is an inert, salt-free substrate with a neutral pH and a high aeration capacity. One thousand and five hundred grams (1500 g) of the medium was put in each pot of 3 L capacity, 16.5 cm diameter and 19.0 cm depth. Holes were made at the bottom of the pots for drainage.

The experiment was set up in a randomized plot design with three replications by increasing the concentrations of NaCl (0, 14.1, 44.4 and 70.4 mM) in the nutrient solution (Korkmaz et al., 2018). The macroelement and microelement levels in the nutrient solution for the tomato plants (Kardelen F_1 variety) were applied according to the methods of Alpaslan et al. (1998). Calcium nitrate tetrahydrate ($Ca(NO_3)_2 \cdot 4H_2O$), potassium dihydrogen phosphate (KH_2PO_4), ammonium nitrate (NH_4NO_3), potassium nitrate (KNO_3), magnesium sulfate heptahydrate ($MgSO_4 \cdot 7H_2O$), magnesium nitrate hexahydrate ($Mg(NO_3)_2 \cdot 6H_2O$), manganese chloride dihydrate ($MnCl_2 \cdot 2H_2O$), boric acid (H_3BO_3), zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$), copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), ammonium molybdate tetrahydrate ($(NH_4)_6Mo_7O_{27} \cdot 4H_2O)$) and iron (Fe)-EDDHA (ethylenediamine-N,N′-bis(2 hydroxyphenylacetic acid)) were used to prepare a nutrient solution at 12.0 mM nitrate (NO_3^-), 1.25 mM dihydrogen phosphate ($H_2PO_4^-$), 0.5 mM ammonium (NH_4^+), 5.25 mM potassium (K^+), 2.75 mM calcium (Ca^{2+}), 1.125 mM magnesium (Mg^{2+}), 0.125 mM sulfate (SO_4^{-2}), 40 μM iron (Fe), 5 μM manganese

(Mn), 30 µM boron (B), 0.75 µM copper (Cu), 4 µM zinc (Zn) and 0.5 µM molybdenum (Mo). The pH of the plant nutrient solution was adjusted to 5.5 with 1.0 M KOH or H_2SO_4 solution. All of the reagents used were of analytical grade.

The application of 150 mL of nutrient solution per day to each pot started at planting and continued until 14/08/2022. After that date, 300 mL of nutrient solution was applied per day to each pot until harvesting finished. The nutrient solutions were applied in the early morning hours. During the experiment, the moisture content of the pots was maintained around field capacity by controlling the drainage of irrigation. The pots were irrigated with tap water twice a day, in the afternoon and in the evening. The trial lasted 90 days.

2.1. Measurements

The fruit yield was measured in the lab using a sensitive scale (Precisa, XB-620M, Switzerland). The fruit yield was calculated for each plant as the cumulative fruit weight and the number of fruits during the six pickings, and then the average fruit weight was calculated. The dry matter content (%) was determined gravimetrically by drying 5 g of tomato homogenate in a laboratory oven (Nüve, ES-500, Turkey) set at 70 °C until a constant weight was reached.

The diameter and height of the intact fruits were measured using a digital caliper (ASIMETO, Series 307). Fruit height was measured from the blossom end to the top of the fruit, and the diameter was taken as the maximum diameter of the equatorial section. Fruit shape index was calculated as vertical diameter divided by horizontal diameter. Every hour, the caliper was washed with water to remove deposited plant parts.

A digital penetrometer (PCE Instruments, PCE-FM 200) with a cone-shaped probe of Φ8 mm was used for firmness measurements in the equatorial zone. The resistance at penetration of the probe was measured and expressed in kgf cm^{-2}.

Colour measurements were taken using a portable colourimeter (CR-300, Konica Minolta, Tokyo, Japan) and data reported as lightness (L*), green to red (a*) and blue to yellow (b*) values of the Cielab scale (Mcguire, 1992). Eeach record was an average of three measurements on every ripe tomato fruit (one at the distal area and two in the equatorial zone). Chroma [$C = (a^{*2}+b^{*2})^{1/2}$] and hue angle [H=arctan (b*/a*)] were calculated from a* and b* values (Lancaster et al., 1997). Moreover, the results were combined as the Tomato Color Index (Hobson et al., 1983) by using equation 1.

$$\text{Tomato Color Index (TCI)} = \frac{(2000 \times a^{*})}{(L^{*} \times \text{C})} \quad (1)$$

2.2. Sampling

Immediately after collection, fully ripened tomato fruits of each replicate were washed in tap water, blotted with a paper towel and halved. The seeds were removed and the pericarp and mesocarp were ground to a homogeneous puree in a blender (MB450, Turkey) for about 2 minutes. Part of the sample was immediately used for some analyses (soluble solids content, titratable acidity, ascorbic acid, lycopene). In addition, the strained juice was filtered with a 120 mm paper filter (Whatman). The clearly filtered juice was used for the pH and EC analyses.

2.3. Analytical Methods

Electrical conductivity (EC) was determined using a conductivity meter (Mettler Toledo Instruments, FiveEasy Plus Cond meter FP30) and expressed in dS/m; pH was determined using a pH meter (Mettler Toledo Instruments, SevenCompact pH meter S220) (AOAC, 1990).

To determine the titratable acidity (TA), 10 mL of filtered tomato juice was titrated with 0.1 N standardized sodium hydroxide (NaOH) solution until equilibrium (pH of 8.1) and the measured TA was expressed as the concentration (%) of citric acid, a major organic acid in tomatoes. The data obtained from the measurements were calculated using equation 2 below.

$$\text{TA}(\%) = \frac{V \times N \times Meq \times 100}{\text{Y}} \quad (2)$$

where; TA = titratable acidity (as % citric acid), V = volume of NaOH used, N = normality of NaOH, Meq = weight of a milliequivalent of citric acid (0.064 g), and Y = volume of tomato extract used (10 mL).

For the determination of total soluble solids, one drop of the clear juice was measured with a digital refractometer Atago PAL-1 (3810), 0.0-53.0 Brix (Tokyo, Japan) and expressed as ºBrix (AOAC, 1990).

2.4. Statistical Analysis

This study was conducted according to the random plots trial design. Statistical analysis was performed using the JMP package version 5.0. Results were presented as means±standard errors (n=3) for the treatments. Differences between means were analyzed by one-way analysis of variance (ANOVA) followed by the LSD test, and the degree of difference was indicated by letters at the 5 % level. Heat map of Pearson's correlation coefficient matrix and principal component analysis of the evaluated attributes were produced by OriginPro 2019b (32Bit).

3. Results

3.1. Yield and Yield Components in Tomato

The effects of increasing concentrations of sodium chloride in the nutrient solution applied to the solid medium on the yield and its components in tomato are given in Figure 1a-c.

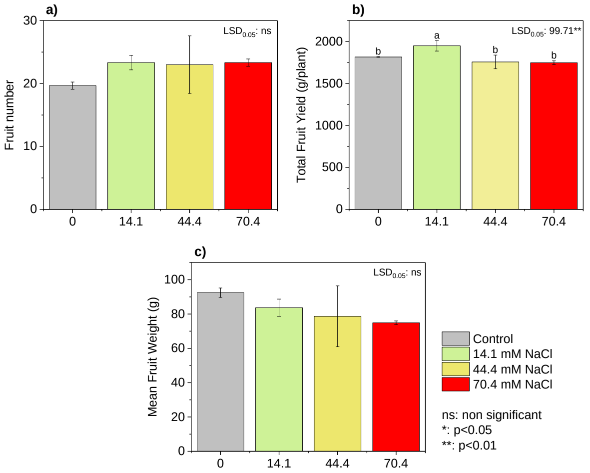

Figure 1a-c. Effect of NaCl concentrations on the yield and its components in tomato. Mean fruit weight (**a**); Fruit number (**b**); Total fruit yield (**c**).

The effect of increasing the NaCl concentration in the nutrient solution on total fruit yield was significant at the $p < 0.01$ level, while the effect on average fruit weight and number of fruits was insignificant. Compared to the control, the 14.1 mM NaCl treatment increased total fruit yield by 7.34%, but the 44.4 mM and 70.4 mM NaCl treatments reduced yield by 3.25% and 3.74%, respectively. However, these decreases were not statistically significant compared to the control.

3.2. Biophysical Quality Characteristics

The effects of increasing concentrations of NaCl in the nutrient solution applied to the solid medium on the biophysical quality characteristics of tomato fruits are given in Table 1.

Table 1. Effect of NaCl Concentrations on the Biophysical Quality Characteristics of Tomato Fruits

NaCl (mM)	Fruit size (mm)	Fruit diameter (mm)	Oven Dry (g)	Dry Matter (%)
0 (Control)	52.5 ± 1.25 ab	60.4 ± 0.59 a	0.86 ± 0,03	2.46±0.10 b
14.1	52.8 ± 1.26 a	59.0 ± 1.10 ab	0.89 ± 0,01	2.64±0.10 b
44.4	48.3 ± 1.02 bc	53.2 ± 1.00 c	0.90 ± 0,02	3.75±0.08 a
70.4	46.9 ± 0.51 c	56.0 ± 0.83 bc	0.83 ± 0,01	3.41±0.07 a
$LSD_{0.05}$	4.21	3.60		0.34
Significance	*	**	ns	**

Each value represents mean ± SE (n = 3); There is no significant difference at 0.05 between means shown with the same letters; ns: Non-significant; *significant at 5%; **significant at 1% level.

The effects of increased NaCl concentration in the nutrient solution on fruit diameter and fruit firmness were significant at the $p < 0.01$ level and on fruit size at the $p < 0.05$ level, while the effect on fruit shape index was insignificant (Table 1). The addition of 14.1 mM and 44.4 mM NaCl to the nutrient solution had no effect on fruit size compared to the control; however, the addition of 70.4 mM NaCl decreased fruit size. Fruit diameter decreased and fruit firmness increased with increasing salt concentration compared to the control (Table 1).

3.3. Organoleptic Quality

3.3.1. Commercial quality characteristics

The effects of increasing concentrations of NaCl in the nutrient solution applied to the solid medium on the commercial quality characteristics of tomato fruits are given in Table 2.

Table 2. Effect of NaCl Concentrations on the Commercial Quality Characteristics of Tomato Fruits

NaCl (mM)	a*	b*	L*	h*	C*	Tomato Color Index
0 (Control)	18.86 ± 0.55 b	26.76 ± 0.67 a	45.49 ± 0.45 ab	54.80 ± 1.39 a	32.77 ± 0.36	25.36 ± 1.12 b
14.1	20.20 ± 0.04 a	25.16 ± 0.01 b	43.47 ± 0.21 c	51.25 ± 0.06 b	32.26 ± 0.03	28.80 ± 0.11 a
44.4	20.76 ± 0.31 a	24.52 ± 0.35 b	46.44 ± 0.23 a	49.74 ± 0.81 b	32.14 ± 0.09	28.40 ± 0.04 a
70.4	20.96 ± 0.08 a	24.63 ± 0.04 b	44.92 ± 0.21 b	49.60 ± 0.10 b	32.34 ± 0.07	28.86 ± 0.08 a
$LSD_{0.05}$	1.27	1.51	1.15	3.22		2.24
Significance	*	*	**	*	ns	*

Each value represents mean ± SE (n = 3); There is no significant difference at 0.05 between means shown with the same letters; ns: Non-significant; *significant at 5 %; **significant at 1 % level.

The effect of increased NaCl concentration in the nutrient solution on the L* value of the fruit skin colour was significant at the $p < 0.01$ level, while the effects on the a* value, b* value, hue angle value, and color index value were significant at the $p < 0.05$ level. However, the effect of increasing the salt concentration in the nutrient solution on the fruit skin colour value was statistically insignificant (Table 2).

In the skin of tomato fruit, the a* value increased and the b* value decreased at NaCl treatments. However, the effects of the different salt concentrations on the a* and b* values of the fruit skin were similar. The L* value of tomato fruit skin decreased when 14.1 mM NaCl was added to the nutrient solution compared to the control.

On the other hand, the values obtained from 44.4 mM and 70.4 mM NaCl treatments were similar to those obtained from the control. The hue angle value of the skin of tomato fruits showed a decrease in the salt treatment compared to the control. However, this decrease was similar for the NaCl concentrations used. In other words, the hue angle values of tomato fruit skins grown with different concentrations of salt application were close to each other. The color index of tomato fruit skin increased with salt treatment compared to the control. This increase was similar at different salt levels (Table 2).

3.3.2. Physico-chemical quality characteristics

The effects of increasing concentrations of NaCl in the nutrient solution applied to the solid medium on the physico-chemical quality characteristics of tomato fruits are given in Figure 2a-e.

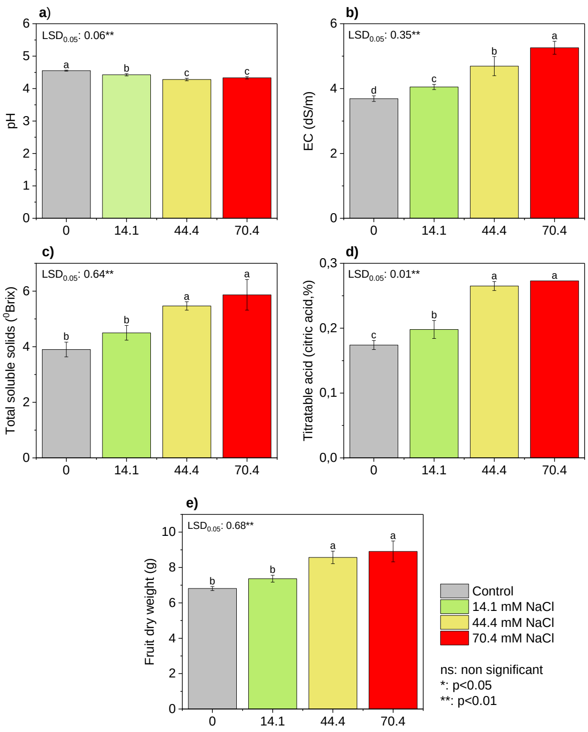

Figure 2a-e. Effect of NaCl concentrations on the physico-chemical quality characteristics of tomato fruits. pH of tomato juice, (**a**); EC of tomato juice (**b**); Total soluble solids (**c**); Titratable acid (**d**); Fruit dry matter (**e**).

The effects of increasing the NaCl concentrations in the nutrient solution on the pH and EC values, the titratable acidity in the fruit juice, and fruit dry matter were significant at the $p < 0.01$ level, while the effect on the total soluble solids (°Brix) in the fruit was significant at the $p < 0.05$ level. As the salt concentration in the nutrient solution increased, the pH of the tomato fruit juice decreased, while the EC value, the total soluble solids and the percentage of titratable acidity of the juice increased compared to the control (Figure 2a-d). At 44.4 mM and 70.4 mM NaCl concentration in the nutrient solution, the pH values of tomato fruit juice were low and similar to the control (Figure 2a). On the other hand, the total soluble solids in the tomato fruits were high and close to each other at medium (44.4 mM) and high (70.4 mM) NaCl concentrations compared to the control (Figure 2c). The dry matter (%) in the fruits increased with increasing NaCl concentration in the nutrient solution. However, these increases were found to be significant at 44.4 mM and 70.4 mM NaCl concentrations compared to the control. Application of 14.1 mM NaCl in the nutrient solution had no significant effect on fruit dry matter compared to the control (Figure 2e).

3.4. Heat Map Pearson Correlation and Principal Component Analysis

The results of the correlation relationships between the yield components and fruit quality characteristics examined in the study are shown in Figure 3. The correlation results revealed that there were significant relationships between the analyzed parameters at the $p < 0.01$ and $p < 0.05$ levels. While b*, h*, TA and FDM showed the most significant correlations, no significant correlation was found for FSI with any of the characteristics analyzed in the study. In addition, the highest positive correlation ($p < 0.01$; 0.98) was found between h* and b*, while the highest negative correlation ($p < 0.01$; -0.98) was found between h* and a*. Moreover, the correlation relationship between b* and FS was the least significant positive relationship (0.59) at $p < 0.05$, while the correlation relationships between FDM and TFP and between TSS and MFW were the least significant negative relationships (-0.58).

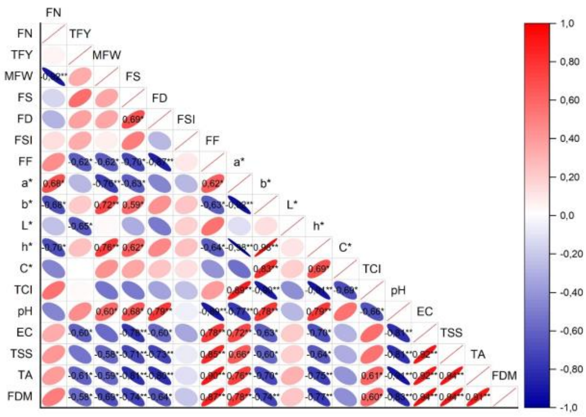

Figure 3. Heat map of Pearson's correlation coefficient matrix between various yield and fruit quality attributes of tomato under NaCl applications. The values in the figure are Pearson's correlation coefficient. * and ** denote correlation coefficients that are significant at $p < 0.05$ and $p < 0.01$ level, respectively. NF: fruit number, TFY: total fruit yield, MFW: mean fruit weight, FS: fruit size, FD: fruit diameter, FSI: fruit shape index, FF: fruit firmness, a*: red/green value, b*:blue/yellow value, L*: lightness, h*: hue angle, C*: chroma, TCI: total color index, pH: potential of hydrogen ions, EC: electrical conductivity, TSS: total soluble soilds, TA: titratable acid, FDM: fruit dry matter.

The principal component analysis of the studied attributes is given in Figure 4. The contributions of different components of PCA are presented on the x-axis (PC1) and y-axis (PC2). PC1 (58.9%) and PC2 (16.9%) exhibited the highest contributions in terms of percentage variance and represented 75.8% of the total variance in the dataset (Figure 4).

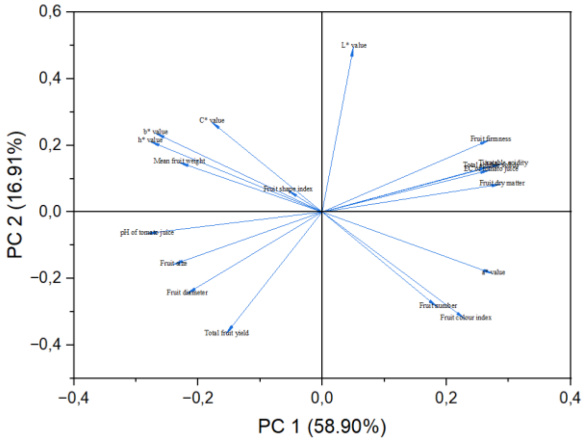

Figure 4. Grouping of the variables in principal components.

Figure 4 shows that the variables fruit firmness, total soluble solids, titratable acidity, EC value in the fruit juice and dry matter content in the fruit are related to each other in the same direction and the relationship between them is strong. The variables fruit hardness, total soluble solids, titratable acidity, EC in the fruit juice and dry matter content in the fruit have an inverse relationship with the variables pH value, fruit length, fruit diameter and yield. There is a positive correlation between the pH value of the fruit juice, the size of the fruit, the diameter of the fruit and the yield variables. The relationship between L* and the yield variables is inverse. The color index of the tomato, a* and the fruit number variables are positive and strongly correlated. Chroma, fruit shape index, average fruit weight, h* and b* are positively correlated. These variables are only weakly correlated with the FSI and the other variables are strongly correlated with each other. Conversely, chroma, fruit shape index, average fruit weight, h* and b* showed a negative correlation with the color index of the tomato, a* and the number of fruits.

4. Discussion

In the present study, the increasing salt concentration in the nutrient solution partially decreased the mean fruit weights, but this decrease was not statistically significant (Figure 1a). The differences in fruit number and weight may also be attributed to how plants allocate their resources under varying salinity conditions. In the absence of additional stress from NaCl, the plants may have prioritized fruit weight over quantity, resulting in fewer but larger fruits. Sánchez-González et al. (2016) reported that high salt levels caused a sharp decrease in the fresh weight of tomatoes. The decrease in fruit weight under saline conditions has been attributed to less water uptake by the root and thus reduced water transport to the fruit (Sakamoto et al., 1999). Likewise, Zhang et al. (2016) reported that salt stress reduced water uptake in the plant root through an osmotic effect and subsequently induced water stress.

Our results, in which we found the effect of increasing salt concentration in the nutrient solution on fruit number to be insignificant (Figure 1b), support the results found by Li et al. (2001) and Ehret et al. (2013). On the other hand, Zhang et al. (2017) observed that the total number of fruits per plant decreased under salinity in tomato plants grown in hydroponic culture.

While total fruit yield increased significantly by 7.34% with the addition of 14.1 mM NaCl to the nutrient solution compared to the control, it decreased by 3.25% and 3.77% with 44.4 mM and 70.4 mM NaCl treatments, respectively. However, these decreases were not statistically significant compared to the control (Figure 1c). Botella et al. (2021) reported that marketable fruit yield in tomato plants under control conditions was 91.8%, while it decreased to 80.5% in those grown under salt stress (60 mM NaCl). Similarly, Moya et al. (2017) reported a decrease in total and marketable fruit yield in tomatoes grown under salinity treatments (EC: 4.5 $dS \cdot m^{-1}$). Salt stress reduces marketable yield by reducing fruit size (Zhang et al., 2022).

Adding NaCl at 14.1 mM and 44.4 mM concentrations to the nutrient solution did not affect fruit size compared to the control; however, NaCl application at a concentration of 70.4 mM significantly reduced fruit size (Table 1). Many researchers have observed that fruit size decreased significantly with increasing salt application doses (Fernández-García et al., 2004; Ehret et al., 2013). Exposure to high salinity lowers the water potential of the plant, reducing water flow to the fruit and ultimately minimizing the rate of fruit expansion (Johnson et al., 1992).

In the present study, the effect of different salt levels in the nutrient solution on fruit shape index was found to be insignificant (Table 1). ''Fruit shape index'' is defined as the ratio of the maximum length of a fruit to its maximum width. Specifically, the rate, duration, and plane of cell division and isotropic and anisotropic cell growth contribute significantly to the eventual morphology of plant organs (Wu et al., 2018). In horticulture, fruit shape is an important feature that not only satisfies people's curiosity but also distinguishes varieties within a given plant species (Wang et al., 2019).

As the salt concentration in the nutrient solution increased, the fruit firmness of the tomato increased compared to the control (Table 1). Reports on the effects of salinity on tomato fruit hardiness have been controversial. Botella et al. (2000), and Schwarz et al. (2001) reported that tomato fruit firmness increased with an increasing salt level in the root zone. Increased fruit firmness depends on the intensity of salt stress and the tomato variety (Ruiz et al., 2015). On the other hand, Krauss et al. (2006) reported that salinity reduces fruit firmness. It was reported that fruit firmness decreased at high salt levels above 10 dS·m^{-1} in the root zone of tomatoes (Cuartero and Fernández Muñoz, 1999). The texture of fresh tomatoes is determined by the firmness of the flesh and the thickness of the skin (Kader et al., 1978). Softening during storage, distribution, and ripening of tomatoes can be a big issue since it increases their vulnerability to harm (Batu, 2004). Fruit cracking is affected by variety, size, firmness, shape, fruit development, fruit cuticle and sugar content, irrigation water quality, and environmental conditions (Abdollah, 2015).

In the current study, the salt treatment mainly showed positive effects on tomato fruit's commercial quality parameters (Table 2). The a* value is a good parameter for the development of the red colour and the degree of maturity of the tomato, while the b* value indicates a yellow discolouration (Artés et al., 1999). Fruit color affects consumer acceptance and perception of taste and aroma (Hoppu et al., 2018; Shen et al., 2018). Chlorophylls and carotenoids accumulated in the epidermis, lower epidermal layer, and pericarp are responsible for the fruit color of tomatoes (Lado et al., 2016; Llorente et al., 2017; Dono et al., 2020).

In the present study, as the salt concentration increased in the nutrient solution, the pH value of tomato fruit juice decreased while the EC value increased compared to the control (Figure 2a-b). Botella et al. (2021) reported that the pH value decreased in tomato fruit juice as salinity increased. On the other hand, it has been reported that the pH and EC values of tomato juice did not change significantly under salt stress compared to the control (Azarmi et al., 2010; Moya et al., 2017).

As the salt concentration increased in the nutrient solution, the total soluble solids content of tomato fruit juice increased compared to the control (Figure 2c). Similar findings were obtained by Ruiz et al. (2015), Huang et al. (2016) and El-Mogy et al. (2018). The increase in soluble solids content of tomato fruit exposed to sodium chloride was also attributed to a reduction in water transport to the fruit. However, it has been reported that the taste of tomato improves with salinity (Nakahara et al., 2019). Regarding human nutrition, salt effects on tomato fruit should not necessarily be seen as unfavorable (Martínez et al., 2020). Total soluble solids (°Brix) are a good indicator of total soluble sugars, and the increase in Brix itself is a consequence of the salt-induced improvement in fruit quality (Sánchez-González et al., 2015; Van Meulebroek et al., 2016). It is well established that manipulating central organic acids is a promising approach to improving fruit yield in tomatoes (Martínez et al., 2020). Citric and malic acid accumulation plays a crucial role in the ripening stage of fruit and can provide sugars to the fruit through neo-glucogenesis (Quinet et al., 2019).

In the present study, titratable acidity increased with an increasing salt concentration in the nutrient solution (Figure 2d). Our results for this parameter were in agreement with the results found by Agius et al. (2022) and Zhang et al. (2022). The positive effect of salinity on tomato quality is due to the high concentration of titratable acid and sugar in the juice (Krauss et al., 2006).

In our study, dry matter in fruits increased significantly at medium (44.4 mM) and high (70.4 mM) NaCl administrations (Figure 2e). According to Sánchez-González et al. (2015), the percentage of dry matter increased in tomato fruits grown at high salinity (0.7 S·m^{-1}) compared to tomatoes grown at low salinity (0.5 S·m^{-1}). In addition, the low dry matter content of the fruit in the control group supports the positive effects of the NaCl treatment on the dry weight of the fruit. Salt treatments can reduce water uptake by creating osmotic stress in the plant, which contributes to an increase in the dry matter content of the fruit. Consequently, controlled salt stress treatments can improve fruit quality by increasing the dry matter content of the fruit. Salt application in soilless agriculture, when applied correctly, can be an effective method for enhancing stress tolerance in plants and achieving higher quality produce. However, the potential risks of this method should also be considered, and the system should be regularly monitored.

5. Conclusion

This study investigated the effects of varying NaCl concentrations in nutrient solutions on the yield and quality of tomato fruits. The application of 14.1 mM NaCl significantly increased total fruit yield. Additionally, moderate NaCl concentrations generally enhanced several quality traits of the fruits. In contrast, higher salt levels led to reductions in fruit size and diameter. These results indicate that the careful management of salt levels in nutrient solutions can effectively improve specific market-desired qualities in tomatoes while maintaining overall yield.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	G.A.	A.K	S.D	S.R	Z.C
C	50	50	-	-	-
D	60	40	-	-	-
S	80	20	-	-	-
DCP	60	-	10	10	20
DAI	50	25	25	-	-
L	60	40	-	-	-
W	100	-	-		
CR	50	40	10	-	-
SR	100	-	-	-	-
PM	100	-	-	-	-

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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