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Salinity Impact on Yield, Quality and Sensory Profile of 'Pisanello' Tuscan Local Tomato (*Solanum lycopersicum* L.) in Closed Soilless Cultivation

Fatjon Cela [1,*], Giulia Carmassi [1], Basma Najar [2], Isabella Taglieri [1,3], Chiara Sanmartin [1,3], Susanna Cialli [4], Costanza Ceccanti [1,3], Lucia Guidi [1,3], Francesca Venturi [1,3] and Luca Incrocci [1]

1 Department of Agriculture, Food and Environment, University of Pisa, Via del Borghetto 80, 56124 Pisa, Italy; giulia.carmassi@unipi.it (G.C.); isabella.taglieri@unipi.it (I.T.); chiara.sanmartin@unipi.it (C.S.); costanza.ceccanti@unipi.it (C.C.); lucia.guidi@unipi.it (L.G.); francesca.venturi@unipi.it (F.V.); luca.incrocci@unipi.it (L.I.)
2 Pharmacognosy, Bioanalysis & Drug Discovery Unit, Faculty of Pharmacy, Free University of Brusseles, Bld Triomphe, Campus Plaine, CP 205/9, B-1050 Bruxelles, Belgium; basma.najar@ulb.be
3 Interdepartmental Research Center Nutrafood-Nutraceuticals and Food for Health, University of Pisa, 56124 Pisa, Italy
4 Crop Science Research Center, Scuola Superiore Sant'Anna, Piazza Martiri della Libertà 33, 56127 Pisa, Italy; susanna.cialli@santannapisa.it
* Correspondence: fatjon.cela@agr.unipi.it; Tel.: +39-0502216531

Abstract: Tomatoes are globally renowned for their nutritional value and culinary versatility. However, environmental stresses, particularly salinity, present significant challenges to tomato production, impacting both yield and fruit quality. In light of these challenges, this study investigates the effect of salinity on yield and fruit quality of a local cultivar tomato named 'Pisanello' in a closed soilless rockwool cultivation system. Total yield, fruit size, and number were investigated in both control (10 mM of NaCl) and salinity-treated plants (salinity 1 (S1)~30 mM of NaCl and salinity 2 (S2)~60 mM of NaCl), alongside various physicochemical parameters in fully ripened tomato fruits. The results indicated a decrease in crop production with rising sodium chloride concentration in the nutrient solution (25% and 41% for S1 and S2 treatment, respectively). Conversely, salinity-treated fruits exhibited an increase in total phenolic content of +21.9% in S1 and +36.7% in S2 and in antioxidant capacity (+33.5% and +34.7%, for the S1 and S2 treatments, respectively). Salinity treatments registered in general higher quality parameters such as titratable acidity (+8.9 for S1 and +16.5% for S2), total soluble solids (+18.5% for S1 and +43.0% for S2) and fruit firmness (+30.7% for S1 and +60.3% for S2) in comparison with control tomato fruits. Sensory profile analysis further validated the preference for fresh consumption of tomato fruits grown with saline water. These findings suggests that salinity stress can enhance the nutritional quality and taste of the Pisanello tomato. Further investigation could explore the optimal NaCl concentration to balance tomato production and nutritional quality.

Keywords: hydroponics; crop production; traditional landrace; saltwater irrigation; greenhouse; tomato quality; functional food; nutraceutical profile; sensory analysis

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1. Introduction

The tomato (*Solanum lycopersicum* L.) stands as one of the most important vegetable crops globally, with almost 5 million hectares of cultivated land dedicated to its cultivation, yielding over 180 million tons of harvested fruits [1]. Italy plays a prominent role in tomato production, ranking among the top 10 tomato producers in the world with an annual production of 5.2 million tons [1]. Tomatoes are a good source of natural antioxidants, such as carotenoids, ascorbic acid, and polyphenols, thus playing an important role in human nutrition [2]. The levels of these bioactive compounds in tomato fruits are influenced by

various environmental and agronomic factors, such as pedo-climatic environment, tomato cultivar, irrigation, and fertilization techniques [3].

Modern tomato cultivars can be severely affected by drought, leading to inhibited seed development and reduced stem and fruit growth [4,5].

Local cultivars or tomato landraces represent adaptive responses to local ecosystems and serve as an excellent resource of fruit nutritional quality, rich in primary and secondary metabolites, including carotenoids and phenols thought to be beneficial for human health [6]. In Italy, numerous traditional varieties of tomato have been selected for their agronomic traits, such as taste, productivity, transportation durability, and marketability [7–9]. Locally adapted Tuscan tomato cultivars, including the Pisanello tomato, demonstrate distinct physiological responses and fruit-level concentrations of polyphenols and antioxidants compared to newly developed tomato varieties [7,8,10–13].

The Pisanello tomato is particularly popular within the Tuscan region, pairs exceptionally well with extra virgin olive oil and bruschetta due to its reduced pulp deliquescence. Nowadays, climate change is causing significant consequences in global agriculture due to various abiotic stresses affecting plants, including crop salinity. It is estimated that approximately 40% of the Earth's surface is currently experiencing water and salt stress, with an expected increase to 50% in the coming years [14]. One advantageous consequence of salinity treatment is the increased sugar content in tomato fruit juice; nevertheless, this can lead to a reduction in fruit size and yield [6,15,16]. Tomatoes are commonly considered a moderately salt-tolerant crop, often cultivated in areas affected by aquifer salinization and subsequent use of saline water for irrigation, such as the Mediterranean basin [17].

Moreover, moderate NaCl concentration in irrigation water typically enhances plant accumulation of primary and secondary metabolites in different tissues, positively affecting tomato fruit quality [15]. High salinity increases tomato juice sugars that are commonly considered a standard tomato fruit quality parameter, according to several studies [6,14,18–20]. Other authors [21,22] demonstrated that the total soluble sugars (TSSs) and citric acid (CA) concentrations increased in tomato fruits grown with salty water.

Azarmi et al. (2010) [23] found that EC above 3.0 dS m^{-1} enhanced titratable acidity (TA) and TSSs in tomatoes grown in hydroponics under salinity treatments (2.5, 3.0, 4.0, 5.0, and 6.0 dS m^{-1}) by adding NaCl to the standard nutrient solution.

Saline treatments enhanced CA and TSS levels, suggesting that salinity improves tomato fruit taste and flavour, according to Rouphael et al. [24].

Overall, tomato fruit quality is strongly related to the salinity of the nutrient solution in soilless cultivation with electrical conductivity serving as a practical and efficient indicator to increase fruit quality by boosting chemical composition and bioactive compounds [24].

Soilless cultivation has emerged as one of the most appropriate cultivation systems for achieving high-quality fruits and vegetables while maximizing water and nutrient efficiency, thereby minimizing losses [25,26]. Hydroponic systems enable the collection and reuse of drainage in closed cultivation systems, effectively preventing the loss of water and nutrients into the environment, such as subterranean and surface water bodies [25,27]. In Mediterranean regions, closed soilless systems that recirculate nutrient solutions have been highly effective under saline conditions, ensuring optimal nutrient utilisation and minimal discharge, while also producing high-quality vegetables [25,28].

While previous research has explored the impact of abiotic stresses, particularly salinity, on tomatoes, this study seeks to delve deeper into understanding the response of a landrace tomato cultivar, Pisanello, to high NaCl concentration in a soilless cultivation system in a greenhouse. Several organoleptic parameters and health-promoting compounds were investigated in fully ripened tomato fruits such as fruit firmness, electrical conductivity (EC), pH of tomato juice, titratable acidity, total soluble solids (TSSs), lycopene and β-carotene content, total phenolic content, and antioxidant activity (DPPH).

To the best of our knowledge, very few data are available in the literature about a validated method for assessing panel tests on fresh tomato fruits. Therefore, a sensory sheet specifically designed for evaluating fresh tomatoes was developed. Additionally, the overall sensory profile of fully ripened tomatoes was examined by trained judges to determine how it might be influenced by treatment, comparing control fruits and fruits grown under high salinity treatments (salinity 1, S1~30 mM of NaCl and salinity 2, S2~60 mM of NaCl added to the nutrient solution).

2. Materials and Methods

2.1. Experimental Setup and Plant Growth Conditions

The experiment was carried out in a greenhouse at the Department of Agriculture, Food and Environment (DAFE), University of Pisa, Italy, with tomato cv. Pisanello grafted on the commercial rootstock 'Maxifort' (*S. lycopersicum* L. × *S. habrochaites* S. Knapp & D.M. Spooner, De Ruiter Seeds, Bergschenhoek, The Netherlands). The tomato plants were grown in rockwool substrate with recirculating nutrient solution.

Tomato seedlings were transplanted on 1 April 2021, into standard (1-m long) rockwool slabs, with each slab accommodating three single-stem plants and five drippers, resulting in a plant density close to 3.2 plants m^{-2}.

The nutrient solution was prepared using tap water or ground water, supplemented with appropriate amounts of analytical grade salts (Carlo Erba Reagents, Milano, Italy). For each salinity treatment, two levels of salt water were prepared by dissolving NaCl in tap water. Approximately 30 plants per treatment were used, with two replicates for each treatment.

The treatments were as follows: control plants (C~10 mM of NaCl), obtained without adding NaCl in the nutrient solution, but only the amount of salt contained naturally in the ground water at 3.00 dS m^{-1}; salinity 1 treatment (S1) at 6.00 dS m^{-1} reaching 30 mM NaCl; and salinity 2 treatment (S2) at 9.00 dS m^{-1} reaching 60 mM NaCl in the nutrient solution. Salt was gradually applied starting 35 days after transplant (DAT) with increments of approximately 1.0 dS m^{-1} (close to 10 mM NaCl) daily to avoid osmotic shock to the tomato plants.

Throughout the tomato cultivation cycle, three distinct nutrient solutions were utilised as follows:

(1) Vegetative stage (ground water) with concentrations (mol m^{-3}) of 11.0 N-NO_3, 1.20 P-PO_4, 8.0 K, 5.0 Ca, 2.5 Mg, 6.8 Na, 6.0 S-SO_4, 5.3 Cl, and (μmol m^{-3}) 40.0 Fe, 1.0 Cu, 8.0 Zn, 10.0 Mn, 30.0 B, and 1.0 Mo.

(2) Flowering and green fruit stage (tap water) with concentrations (mol m^{-3}) of 11.0 N-NO_3, 1.20 P-PO_4, 5.0 K, 5.0 Ca, 1.0 Mg, 1.0 Na, 2.0 S-SO_4, 1.5 Cl, and (μmol m^{-3}) 30.0 Fe, 1.0 Cu, 5.0 Zn, 10.0 Mn, 30.0 B, and 1.0 Mo.

(3) Fruit production stage (tap water) with concentrations (mol m^{-3}) of 10.0 N-NO_3, 1.20 P-PO_4, 5.7 K, 4.5 Ca, 0.6 Mg, 1.0 Na, 2.0 S-SO_4, 1.5 Cl, and (μmol m^{-3}) 30.0 Fe, 1.0 Cu, 5.0 Zn, 10.0 Mn, 30.0 B, and 1.0 Mo.

The pH of the recirculating nutrient solution was monitored and kept between 5.50 and 6.50 by adjusting with sulphuric acid when needed. The solution was discharged whenever EC exceeded 4.5, 7.5, and 10.5 mS cm^{-1} for C, S1, and S2 plants, respectively.

Environmental parameters such as temperature, relative humidity, and the solar irradiance were constantly monitored inside the greenhouse using a climate station device (https://www.evja.eu/solutions accessed on 18 May 2024). The mean air temperature during the cultivation cycle was 25.2 °C (with T_{min} = 18.4 °C and T_{max} = 31.8 °C), and the mean relative humidity was about 58.3% (with RH_{min} = 27.3% and RH_{max} = 84.0%). The mean daily global radiation inside the greenhouse was 12.20 MJm^{-2} (with GR_{min} = 2.27 MJm^{-2} and GR_{max} = 17.85 MJm^{-2}).

Crop water requirement was measured daily with a water meter across all treatments.

A drainage fraction of 0.50–0.60 was applied to each irrigation event during the growing season to maintain a constant EC of the nutrient solution in the mixing tank and

the tomato root zone in the rockwool slabs as explained by Carmassi et al. [29]. Aliquots of fresh tomato material were immediately utilised to perform organoleptic analysis whilst other aliquots were frozen in liquid nitrogen and stored until the biochemical analysis.

2.2. Biomass Production, Fruit Yield and Organoleptic Quality

During the cultivation cycle, tomato plants were used for leaf and stem destructive measurements. In order to measure the production of fresh and dry weight above ground in Pisanello tomato crops during the growing season, two plants were harvested, once for each treatment, with two replicates of each treatment.

The dry matter content (DMC) of each biomass component (stem, leaf, and fruit) was determined by weighing all fresh material of each component and after drying samples at 70 °C until constant weight was reached.

Marketable yield was evaluated according to standard practices typically used for Pisanello tomatoes; fruits weighing less than 70 g were not considered marketable. Randomly selected fruits were evaluated to determine various organoleptic quality parameters such as fresh fruit weight (g), total yield (kg m^{-2}), number of fruits affected by blossom end rot (BER) physiological disorder, DMC (%), and pulp hardness or firmness (kg cm^{-2}).

Tomato fruit firmness was assessed on samples of commercial fruits for each treatment, using a digital penetrometer (mod. 53205 TR Turoni & Co., Forlì, Italy) equipped with an 8 mm diameter tip. The maximum force (kg) of the tomato pulp was recorded. Three measurements were performed for each fruit, and the mean value was subsequently calculated for representativeness.

Following fruit firmness measurements, the tomato fruits were cut into small pieces and blended. A part of the puree was dried in an oven to obtain the DMC. This was achieved by placing almost 100 g of fresh tomato puree in a laboratory oven (Memmert GmbH + Co. KG Universal Oven UN30, Schwabach, Germany) at 70 °C until a constant weight was reached, indicating the complete removal of moisture allowing for the determination of the percentage of the DMC.

Another portion of the tomato puree was centrifuged at 3500 rpm for 15 min to obtain the supernatant, which was used to determine the titratable acidity, pH, and EC, as well as the TSSs. The pH value was determined using a bench pH meter (XS pH50+ DHS XS Instruments, Carpi, Italy) with automatic temperature compensation. The EC value was measured using a bench EC meter with automatic temperature compensation (XS COND 51+ XS Instruments, Carpi, Italy). TSSs were determined by refractometer (model ABBE-REF 1, PCE Instruments, Meschede, Germany) and expressed as °Brix. Titratable acidity (TA) was determined by titrating against 0.1 M NaOH solution using phenolphthalein as an indicator and expressed as grams of citric acid per 100 g^{-1} fresh weight (FW).

2.3. Mineral Composition Analysis

The dried samples of tomato fruits were ground into a powder using a mortar. The oven-dried samples were then subjected to wet digestion in a mixture of nitric and perchloric acids (HNO_3:$HClO_4$ 5:2 v/v) at 230 °C for 1 h. Potassium, calcium, magnesium, and sodium were quantified by atomic absorption spectrometry (Varian Model Spectra AA240 FS, Melbourne, Australia), while phosphorous was determined by spectrophotometry using the molybdenum blue method [30]. Nitrogen content was determined by the micro-Kjeldahl procedure [31].

2.4. Total Phenolic Content

Frozen materials of tomato fruits (0.1 g) were homogenised with 1 mL 80% (v/v) methanol solution and sonicated for 30 min at 4 °C. Samples were centrifuged at 10,000× g for 15 min at 4 °C, and the supernatants were collected.

The total phenolic content was determined by the Folin–Ciocalteu (FC) method described by Dewanto et al. [32], with minor modifications, using the Ultrospec 2100 Pro spectrophotometer (GE Healthcare Ltd., Little Chalfont, UK). For the analysis, 10 µL of

the sample was mixed with 125 µL of the FC reagent and 115 µL of distilled water in a cuvette. The mixture was then incubated at 25 °C for 6 min before adding 1.25 mL 7% (*w*/*v*) Na_2CO_3 solution. The samples were then incubated for 90 min in the dark, after which the absorbance was measured at 760 nm. The total phenolic content was expressed as milligram equivalents of gallic acid (GAE) per 100 g^{-1} FW.

2.5. 2,2-Diphenyl-1-Picrylhydrazyl Hydrate (DPPH) Free Radical Scavenging Assay

The DPPH free radical scavenging capacity of each tomato fruit sample was determined according to the method described by Brand-Williams et al. [33]. Briefly, a 3.12 × 10^{-5} M DPPH solution diluted in 80% (*v*/*v*) methanol solution was prepared. For the assay, the same extract used for total phenolic content determination was utilised. Specifically, 10 µL of the extract was added to 990 µL of methanolic DPPH solution. After 30 min of incubation, the change in absorbance at 515 nm was measured. The antioxidant activity based on the DPPH free radical scavenging ability of the extract was expressed as mg Trolox Equivalents (TE) per 100 g^{-1} FW.

2.6. Lycopene and β-Carotene Analysis

The lycopene content in tomato fruit was extracted using a hexane:ethanol:acetone (2:1:1; *v*:*v*:*v*) mixture following the method of Adejo et al. [34]. A frozen aliquot (0.1 g) of tomato sample was dissolved in 1 mL of distilled water, vortexed and incubated in a water bath at 30 °C for 1 h. Then, 8.0 mL of the mixture was added, and samples were vortexed again. After incubation in a dark cupboard for 60 min, 1 mL of distilled water was added to each sample. Samples were vortexed and incubated again in the dark until the separation into two phases. The absorbance of the upper layers of samples were spectrophotometrically read at 503 nm. The lycopene content of extracts was expressed as mg 100 g^{-1} FW. The β-carotene content was performed following the method described by Porra et al. [35], with minor modifications. Fresh samples (0.1 g) were extracted in 4 mL of 80% (*v*/*v*) acetone solution and agitated in the dark at 4 °C for 3 days. The β-carotene content was determined by the increase in absorbance at 663, 648, and 470 nm against a blank solution of acetone 80%, and β-carotene content was expressed as mg 100 g^{-1} FW.

2.7. Sensory Profile

The sensory profiles of the tomato fruits were determined by a descriptive analysis conducted by a panel of trained assessors. The panel consisted of 10 assessors (6 females and 4 males, aged between 23 and 65 years) who were included in the 'expert panel' of the DAFE of the University of Pisa. The panellists were trained using the two-step intensive training as validated and described by Billeci et al. [36], following the Good Senses commercial procedure [37]. Before the start of the specific tasting sessions, a specific training session was organised aimed at defining the specific method of the sensory evaluation of tomato fruits. All of the trained panellists were preliminarily involved in a consensus panel specifically aimed at generating descriptors and their definitions. A final set of 24 descriptive parameters, including both quantitative and hedonic attributes, was individuated by agreement among panellists and an innovative sensory wheel specific for the tasting of tomatoes was developed (Figure 1).

Panel test was arranged in the morning, in a well-ventilated quiet room and in a relaxed atmosphere. Fully ripe tomato fruits were assessed 2 h after being taken out of the fridge. Each tomato fruit was randomly labelled with a three-digit numeric code and provided to assessors in a double-blind presentation to avoid any expectation error [38].

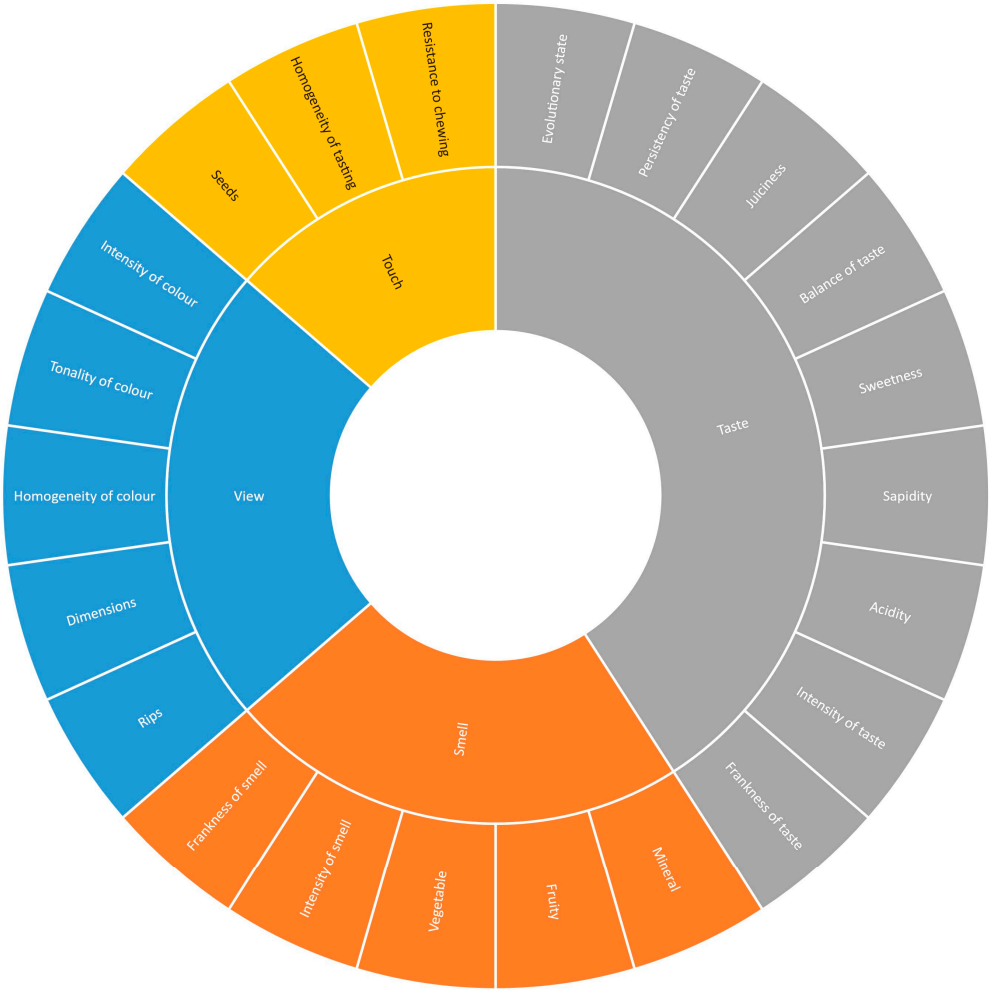


Figure 1. Sensory wheel specifically developed for tomatoes' panel test.

2.8. Statistical Analysis

The data were analysed by one-way analysis of variance (ANOVA) using the salinity treatments as variability factor, and mean values were separated using the Least Significant Differences post-hoc test (LSD; $p = 0.05$). For this purpose, the software program Statgraphics Centurion XV.II-X64 (Manugistic Co., Rockville, MD, USA) was used to perform the statistical analysis.

A two-way ANOVA with samples and panellists as main factors was performed using Big Sensory Soft 2.0 software (ver. 2018) specifically developed for sensory data analysis [39]. The biochemical and sensorial results were subjected to thorough multivariate statistical analyses using JMP software (SAS Institute Imc. JMP. Version 16, SAS Institute Inc, Cary, North Carolina, USA, 2021). Principal Component Analysis (PCA) was conducted on dataset consisting of 6 variables representing treatment types and 9 observations of measured biochemical parameters. This analysis utilised a correlation matrix to determine eigenvalues and eigenvectors. Subsequently, a plot was generated by selecting the two principal components exhibiting the highest variance. Furthermore, a two-way Hierarchical Cluster Analysis (HCA) was conducted using Ward's method, with squared Euclidean distances serving as a metric for similarity.

3. Results and Discussion

3.1. Crop Water Consumption, Biomass Production and Fruit Yield

The cumulative evapotranspiration (ET) measured during the growing period from 6 May 2021 to 22 July 2021, from 35 to 112 days after transplant (DAT) was found to be

397.97 ± 1.65, 377.12 ± 1.56, and 317.25 ± 1.20 L m^{-2} for C, S1, and S2, respectively. A high level of NaCl accumulation in the plant cells contributed to a decrease in cell water potential, resulting in reduced water uptake and more accumulation of soluble sugars in the tomato fruits [14,24,40,41]. The EC levels measured during the cultivation cycle (from 35 DAT to 112 DAT) were 3.14 ± 0.37 dSm^{-1}, 6.19 ± 0.46 dSm^{-1}, and 9.22 ± 0.75 dSm^{-1} for C, S1, and S2, respectively.

The S1 and S2 treatments induced a significant effect on several parameters such as plant biomass (leaves and stem), total yield, the number of marketable fruits, and fruit weight in comparison with the control. However, no differences were registered for the total number of fruits (Table 1).

Table 1. Plant biomass, fruit yield, blossom end rot (BER) fruits, and marketable parameters of tomato fruits grown in hydroponic rockwool system with different salt concentrations of nutrient solution: 10 mM, 30 mM, and 60 mM of NaCl.

Treatment	Plant DW (g)	Total Yield (kg m^{-2})	Total Fruit No. m^{-2}	Marketable Fruit No. Plant m^{-2} (>70 g)	Fruit Weight (g)	Non-Marketable Fruit No. m^{-2} (<70 g)	BER Fruit No. m^{-2}	BER Fruit kg m^{-2}	Marketable Yield (kg m^{-2})
10 mM NaCl	203.5 ± 3.1 a	11.2 ± 0.5 a	94.0 ± 5.5 a	68.1 ± 4.9 a	127.4 ± 6.5 a	19.7 ± 0.7 b	6.2 ± 1.0 b	0.5 ± 0.1 b	8.9 ± 0.4 a
30 mM NaCl	179.5 ± 3.5 b	8.4 ± 0.9 b	81.8 ± 8.1 a	55.7 ± 1.3 b	105.9 ± 4.2 b	20.4 ± 0.1 ab	5.7 ± 0.7 b	0.5 ± 0.1 b	7.6 ± 0.2 b
60 mM NaCl	160.1 ± 3.9 c	6.6 ± 0.6 c	84.7 ± 9.1 a	52.2 ± 2.3 b	85.6 ± 2.8 c	24.3 ± 1.4 a	8.2 ± 0.6 a	0.6 ± 0.1 a	5.7 ± 0.3 c
LSD	15.78	0.76	24.27	10.46	10.31	3.44	1.80	0.08	0.38
Significance	**	***	NS	*	***	*	*	*	***

Data were analysed by one-way ANOVA considering saline treatments as variables. NS, *, **, ***, are not significant; there is significance at $p < 0.05$, 0.01, and 0.001, respectively. The mean values ($n = 3$) ± standard errors with different letters are significantly different ($p < 0.05$) according to the LSD test.

At the end of cultivation cycle (112 DAT), the DMC of the tomato plants (leaves and stem) registered a significant reduction (−11.8% for S1 and −21.3% for S2) in comparison to the control plants (Table 1). The dry weight of the tomato plants reduces when saline stress levels increase, leading to less growth [42,43].

The total tomato yield showed a significant decrease (−25.0% for the S1 and −41.1% for the S2 treatment) in comparison with the control plants (Table 1). Osmotic stress induced by sodium chloride generally limits the accumulation of carbon, adversely affects the expansion of plant tissue, and results in a decrease of the biomass and yield [44].

Plants subjected to the S2 treatment showed significantly lower fruit weight in comparison with the C plants (−32.8%) and S1 plants (−16.9%), (Table 1).

The S2 plants yielded significantly lower marketable production compared to the C plants (−36.0%) and S1 plants (−25.0%). In accordance with the findings of Madugundu et al. [45], the low-salinity (EC 2.5 dS m^{-1}) treatment resulted in the highest tomato fruit yield, which was about 27.6 kg m^{-2}. Conversely, the high-salinity (EC 9.0 dS m^{-1}) treatment caused a reduction in fruit yield to 15.6 kg m^{-2} in three commercial greenhouse tomato cultivars: Ghandowra-F1 (Enza Zaden, Enkhuizen, The Netherlands), Valouro-RZ (Rijk Zwaan, De Lier, The Netherlands), and Feisty-Red (Seminis, St. Louis, MO, USA) grafted onto the commercial rootstock Maxifort [45].

The fruit size gradually decreased with increasing salinity in the nutrient solution used for fertigation (Figure 2).

Subsequently, a significant reduction (−14.6% for S1 and −36.0% for S2) in marketable yield was observed in comparison with fruits from the C plants (Table 1). Our data confirm that the fruit weight and marketable yield of the Pisanello tomato landrace were strongly affected by the salinity. These findings agreed with previous studies [6,40,46], which reported a positive correlation between high salinity and low tomato fruit production.

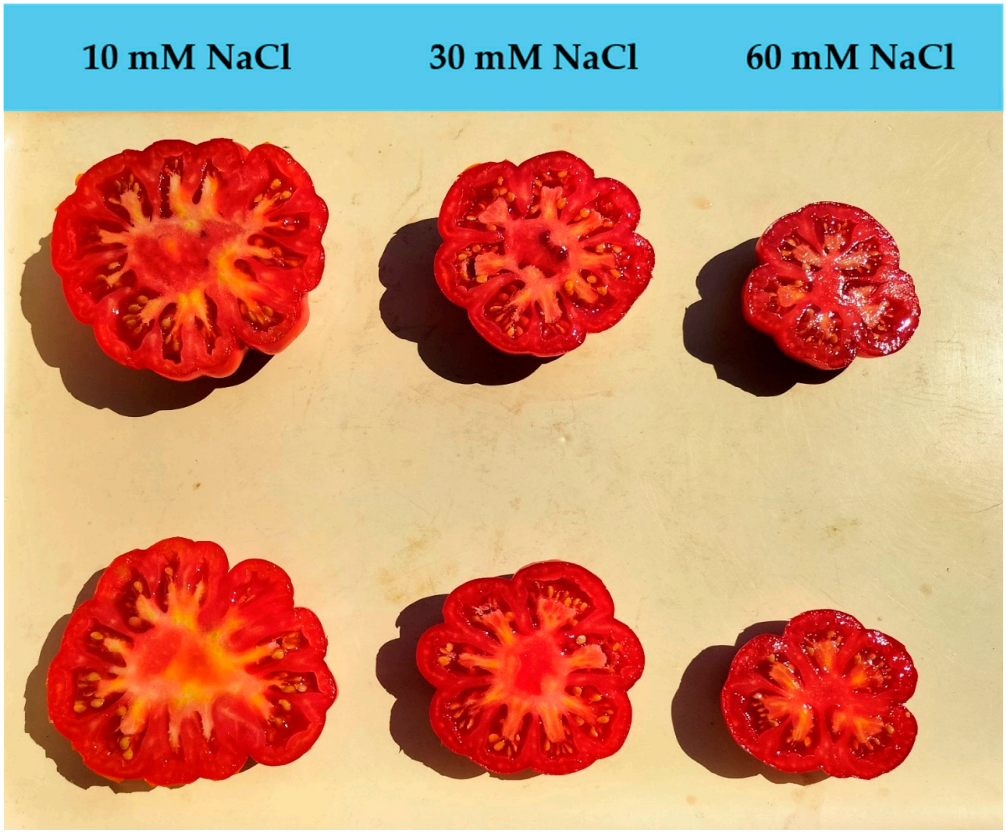


Figure 2. Tomato fruit (cv Pisanello) at harvest grown with different concentrations of salinity; from left to right): 10 mM of NaCl, 30 mM of NaCl, and 60 mM of NaCl.

Both the S1 and S2 treatments registered a higher number of non-marketable fruits and BER in comparison with the C plants (Table 1). Particularly, the S2 treatment showed the highest incidence of BER compared to the S1 treatment and the C, with reductions of −32.3% and −43.9%, respectively (Table 1). These results were consistent with the results of Magán et al. [40], who observed a linear correlation between the number of non-commercial fruits with BER symptoms in seven levels of EC in the nutrient solution in the range between 2.5 and 8.0 dS m^{-1} in two tomato cultivars, 'Daniela' and 'Boludo'.

3.2. Organoleptic Quality and Mineral Content of Tomato Fruits

Concerning fruit quality, the S1 and S2 treatments had a significant impact on lowering the pH values in the tomato juice. Additionally, these treatments underlined higher EC values compared to the control, as shown in Table 2. The control plants showed higher values of pH in the tomato juice (4.19) followed by the S1 treatment (4.13), while the S2 treatment registered the lowest pH value in the tomato juice (4.10), (Table 2).

A recent study found similar results in cherry tomatoes, where the pH of the juice decreased in a rockwool soilless cultivation as NaCl concentration increased in the nutrient solution (0, 17, and 34 mM) [47]. Margan et al. [40] also observed a linear correlation between decreasing pH in tomato juice and increasing salinity in three experiments.

Both the S1 and S2 treatments significantly affected the EC of tomato juice, with higher values compared to the control tomatoes (Table 2). This trend aligns with the findings of Moles et al. [6] who observed an increase in the EC of tomato juice with different salt concentrations (60 mM and 120 mM NaCl) in comparison with control tomato fruits in three southern Italian tomato landraces (Ciettaicale, Linosa, and Corleone) and one commercial cultivar (UC-82B). High salinity can enhance osmotic stress caused by salt, potentially affecting ion uptake in the tomato plant [15,16,24,46,48].

Table 2. Quality parameters of tomato fruits grown in hydroponic rockwool system with different salt concentrations of nutrient solution: 10 mM, 30 mM, and 60 mM of NaCl.

Treatment	pH Juice	EC Juice (dS m^{-1})	TA (g Citric Acid 100 g^{-1} FW)	TSS (°Brix)	DMC (%)	Fruit Firmness (kg cm^{-2})
10 mM NaCl	4.19 ± 0.01 a	10.01 ± 0.04 c	0.79 ± 0.01 c	5.47 ± 0.07 c	6.08 ± 0.07 c	1.01 ± 0.05 c
30 mM NaCl	4.13 ± 0.01 b	10.65 ± 0.02 b	0.86 ± 0.01 b	6.48 ± 0.05 b	6.45 ± 0.02 b	1.32 ± 0.07 b
60 mM NaCl	4.10 ± 0.01 c	12.14 ± 0.08 a	0.92 ± 0.01 a	7.18 ± 0.07 a	7.82 ± 007 a	1.6 ± 0.09 a
LSD	0.02	0.19	0.02	0.22	0.22	0.25
Significance	***	***	***	***	***	**

Data were analysed by one-way ANOVA considering saline treatments as variables. **, ***, are not significant; there is significance at $p < 0.05$, 0.01, and 0.001, respectively. The mean values ($n = 3$) ± standard errors with different letters are significantly different ($p < 0.05$) according to the LSD test.

The S2 treatment induced a significantly higher level of TA, with increases of 16.5% and 8.9% compared to the C plants and S1 plants, respectively (Table 2).

This observation is consistent with the findings by Krauss et al. [19] and Zhang et al. [49] who reported an increase of TA with salt enrichment in nutrient solution.

In our study, the S2 treatment induced higher TSSs compared to the control plants and the S1 treatment, with increases of 43.0% and 20.7%, respectively, in line with those reported by Agius et al. and Petersen et al. [47,50]. This increase in TSSs can contribute to a perceived sweetness in tomato fruits, improving their sensory perception [50].

Similar results were found in the report of Pašalić et al. [51], where the TSS and TA contents in tomato fruits (cv. Buran F1 grafted on Maxifort rootstock) were higher at a salinity level of 6.8 dS m^{-1} in soil, compared with values determined in fruits grown in soil with an EC of 1.7 dS m^{-1}, while Azarmi et al. [23] showed that TA and TSSs significantly increased at an EC above 3.0 dS m^{-1}. Several studies confirmed the strong correlation between high salinity and the increase of sugars in the tomato juice [6,14,18–22].

In a recent study, TA and TSSs increased under saline treatments, suggesting the positive effects of salinity on the taste and flavour of tomato fruits [24].

The DMC increased gradually while increasing NaCl in the nutrient solution, with higher values observed in the S2 treatment, with +28.6% and +21.2% in comparison with the C plants and S1 treatment plants, respectively. Krauss et al. [19] investigated three different salt levels (EC 3.0, 6.5 and 10.0 dS m^{-1}) in hydroponically grown tomatoes (cv. Durinta) and reported that dry weight increased highly and significantly with increasing salt stress from 4.74% (control, EC 3.0 dS m^{-1}) to 5.43% (EC 6.5 dS m^{-1}) and 6.7% (EC 10.0 dS m^{-1}). Fruit firmness was significantly lower in the C plants (1.01 kg cm^{-2}) compared to the S1 (1.32 kg cm^{-2}) and S2 plants (1.68 kg cm^{-2}), showing decreases of −23.5% and −39.9%, respectively (Table 2). Many authors found a relationship between salt accumulation in tomato fruits and fruit firmness [18,22,48,52,53]. Concerning the mineral content of the tomato fruits, no differences were registered for nitrogen and phosphorus content in the fruits (Table 3).

A significant decrease in calcium (−8.0% for S1 and −16.4% for S2) and potassium (−19.4% for S1 and −35.2% for S2) were found compared to the C plants (Table 3). This reduction is attributed to the high salt level affecting mineral uptake in the tomato plants. A similar trend was also reported by several previous studies [20–22,54,55]. The magnesium content in the tomato fruits was also affected by the salinity, with a decrease of −9.6% in the S1 plants and −23.5% in the S2 plants in comparison to the C plants (Table 3). This reduction in Mg concentration due to increased salinity aligns with other studies [54,56].

The sodium content in the tomato fruits was higher than +35.8% in the S1 plants and +129.1% in the S2 plants in comparison to the C plants (Table 3). This tendency was registered in many other studies [21,47,54–57], where the sodium content in tomato fruits increased when the salinity of the growing media increased. High-salinity grown tomatoes accumulate more sodium (Na^+) and chloride (Cl^-) in the plant tissues, and

consequently, have difficulty absorbing crucial nutrients (K^+, Ca^{++}, Mg^{++}, and NO_3^-), reducing vegetative development and yield [45,58,59].

Table 3. Mineral content in tomato fruits grown in hydroponic rockwool system with different salt concentrations of nutrient solution: 10 mM, 30 mM, and 60 mM of NaCl.

Treatment	N g kg^{-1} DW	P g kg^{-1} DW	K g kg^{-1} DW	Ca g kg^{-1} DW	Mg g kg^{-1} DW	Na g kg^{-1} DW
10 mM NaCl	41.2 ± 0.1 a	4.85 ± 0.44 a	47.5 ± 1.4 a	7.31 ± 0.37 a	1.15 ± 0.01 a	1.34 ± 0.05 c
30 mM NaCl	38.0 ± 1.4 a	4.00 ± 0.36 a	43.7 ± 0.4 b	5.89 ± 0.16 b	1.04 ± 0.03 b	1.82 ± 0.02 b
60 mM NaCl	39.9 ± 0.1 a	3.79 ± 0.23 a	39.7 ± 0.2 c	4.74 ± 0.16 c	0.88 ± 0.01 c	3.07 ± 0.17 a
LSD	3.75	1.58	3.76	1.12	0.08	0.46
Significance	NS	NS	*	*	**	**

Data were analysed by one-way ANOVA considering saline treatments as variables. NS, *, ** are not significant; there is significance at $p < 0.05$, 0.01, and 0.001 respectively. The mean values ($n = 3$) ± standard errors with different letters are significantly different ($p < 0.05$) according to the LSD test.

3.3. Nutraceutical Quality of Tomato Fruits

Regarding some of the health-promoting compounds analysed, such as the total phenolic content and antioxidant activity (DPPH), significant differences between the control tomato fruits and the salinity treatments were found (Table 4).

Table 4. Total phenols, antioxidant capacity, lycopene, and β-carotene contents of tomato fruits grown in hydroponic rockwool system with different salt concentrations of nutrient solution: 10 mM, 30 mM, and 60 mM of NaCl.

Treatment	Total Phenolic Content mg GAE 100 g^{-1} FW	DPPH mg TE 100 g^{-1} FW	Lycopene mg 100 g^{-1} FW	β-Carotene mg 100 g^{-1} FW
10 mM NaCl	58.1 ± 3.1 b	41.2 ± 1.2 b	7.2 ± 0.3 a	0.94 ± 0.06 a
30 mM NaCl	70.8 ± 2.0 a	55.0 ± 3.9 a	7.6 ± 0.5 a	1.02 ± 0.02 a
60 mM NaCl	79.4 ± 3.0 a	55.5 ± 2.5 a	6.3 ± 0.4 a	1.07 ± 0.02 a
LSD	9.61	9.52	1.38	0.14
Significance	**	*	NS	NS

Data were analysed by one-way ANOVA considering saline treatments as variables. NS, *, ** are not significant; there is significance at $p < 0.05$, 0.01, and 0.001, respectively. The mean values ($n = 3$) ± standard errors with different letters are significantly different ($p < 0.05$) according to the LSD test.

The total phenolic content was higher in the S1 (+21.9%) and S2 (+36.7%) fruits in comparison with the C fruits. These results are consistent with findings from other studies [41,57,60].

Even the antioxidant capacity was higher in fruits from the S1 and S2 groups (+33.5 and +34.7%, respectively; Table 4). This result agreed with [55], who reported significantly higher total antioxidant activity in tomato fruits from plants grown under salinity stress compared to control fruits.

Moreover, Krauss et al. [19] observed an increase in the total phenolic content and antioxidant activity of fresh tomato fruits from plants cultivated by increasing the EC of the nutrient solution (by adding 17 and 34 mM of NaCl).

However, no significant differences were observed in the lycopene content of the control and treated tomato fruits (Table 4) as reported by other authors in tomato fruits treated with two NaCl salinity levels in a nutrient solution (EC 3.0 and 6.0 dS m^{-1}) [61].

Similarly, the β-carotene content of the tomato fruits did not show any significant difference between the control and treated fruits (Table 4), in line with the results obtained by Fernández-García et al. [62], who studied two tomato cultivars ('Fanny' and 'Goldmar') exposed to 0, 30, or 60 mM NaCl. Some authors [63] showed that salinity stress can lead to similar or higher values of β-carotene in tomato fruits, correlating this trend to the tomato

genotype, while other studies [64] registered a reduction of β-carotene content by 18.6% in a tomato landrace grown in high salinity conditions.

A negative correlation between salinity (the independent variable) and tomato yield parameters (the dependent variables), (plant DW, total yield, marketable yield, and fruit weight) is shown in Table 5 in linear regression equations.

Table 5. Linear regression equations between salinity as independent variable and main dependent variables.

Dependent Variable	Equation	R^2 Value	Significance
Plant DW (g)	y = −0.724x + 224.49	0.959	**
Total yield (kg m^{-2})	y = −0.750x + 13.233	0.976	***
Marketable yield (kg m^{-2})	y = −0.535x + 10.613	0.985	***
Fruit weight (g)	y = −0.746x + 148.4	0.983	***
EC juice (dSm^{-1})	y = 0.356x + 8.802	0.942	***
TA (g citric acid 100 g^{-1} FW)	y = 0.021x + 0.732	0.957	***
TSS (°Brix)	y = 0.286x + 4.661	0.974	***
DMC (%)	y = 0.289x + 5.047	0.887	***
Fruit firmness ($kgcm^{-2}$)	y = 0.106x + 0.711	0.829	**
Total phenolic content (mg GAE 100 g^{-1} FW)	y = 3.543x + 4.819	0.822	**
DPPH (mg TE 100 g^{-1} FW)	y = 2.331x + 36.480	0.563	*

Data were analysed by one-way ANOVA considering saline treatments as variables. *, **, ***, are not significant; there is significance at $p < 0.05$, 0.01, and 0.001, respectively. The mean values ($n = 3$) ± standard errors with different letters are significantly different ($p < 0.05$) according to the LSD test.

Tomatoes cultivated under high salinity accumulate more NaCl in their leaves, stems, and fruits, which makes it harder for the plant to absorb essential nutrients, consequently limiting vegetative growth and yield [45,58,59].

The photosynthetic rate of tomato plants may also be affected by moderate salinity [65]. On the other hand, a positive correlation was registered between salinity (the independent variable) and several physicochemical parameters (EC juice, TA, TSS, DMC, fruit firmness, total phenolic content, and DPPH) (the dependent variables) (Table 5).

By controlling the concentration and composition of the nutrient solution, it is possible to easily implement a eustress, such as mild to moderate salinity, in order to increase the nutritional value of fruits and vegetables [24,66].

3.4. Sensory Profile

The sensory profile of fully ripened tomatoes grown under different salinity treatments was investigated and parameters showing statistically significant differences are reported in Figure 3**.**

Figure 3 illustrates that most sensory parameters pertaining to sight, smell, and taste were notably influenced by the treatment, with the control group exhibiting the least favourable sensory profile. Specifically, tomatoes cultivated with 60 mM of NaCl generally exhibited the most favourable sensory profile compared to those with 30 mM of NaCl and with 10 mM of NaCl (Figure 3).

To delve deeper, both high salinity treatments (30 mM and 60 mM of NaCl) notably enhanced the visual appearance of the fruits by augmenting colour intensity, uniformity, and tonality (Figure 3).

Furthermore, both the 30 mM and 60 mM of NaCl treatments significantly enhanced olfactory frankness along with perfume intensity (Figure 3).

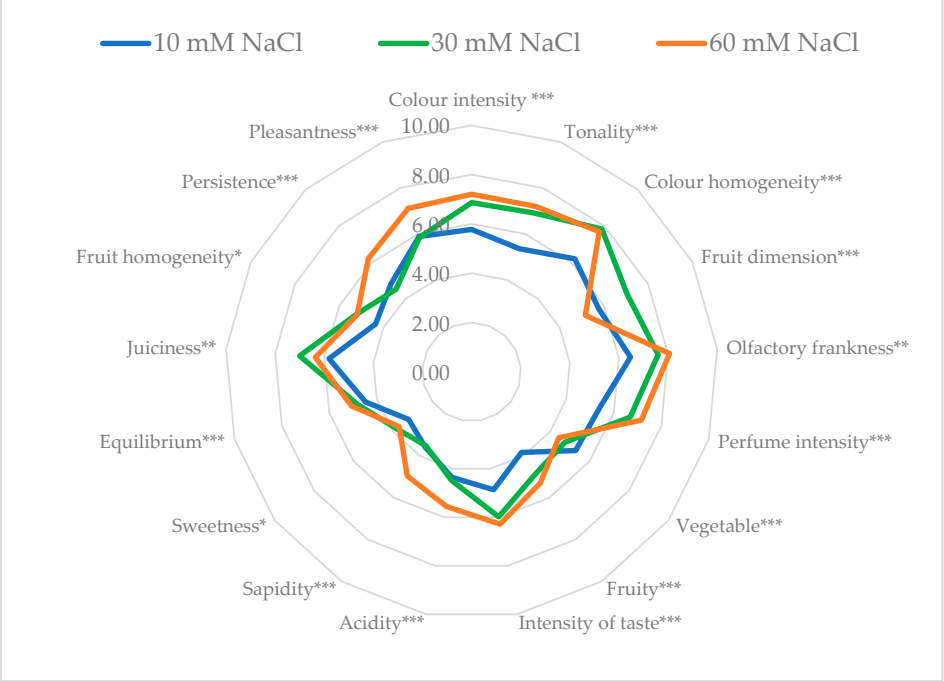


Figure 3. Sensory profile analysis comparison between tomato fruits grown with different salt concentrations of nutrient solution: 10 mM, 30 mM, and 60 mM of NaCl. Significance level *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ based on ANOVA and Tukey post-hoc tests performed between treatments.

As expected, the impact of heightened salinity during fruit growth in the 30 mM and 60 mM of NaCl treatments were clearly evident in the taste profile (Figure 3). There were improvements in taste intensity, primarily associated with increased sapidity and acidity, accompanied by a slight increase in sweetness. This led to an enhanced taste balance and juiciness.

All in all, the tomato fruits grown with 60 mM of NaCl received the highest overall pleasantness score (7.11), closely followed by 30 mM of NaCl (6.14), indicating their potentially greater acceptability among consumers compared to tomatoes grown with 10 mM of NaCl (C = 5.89), (Figure 4).

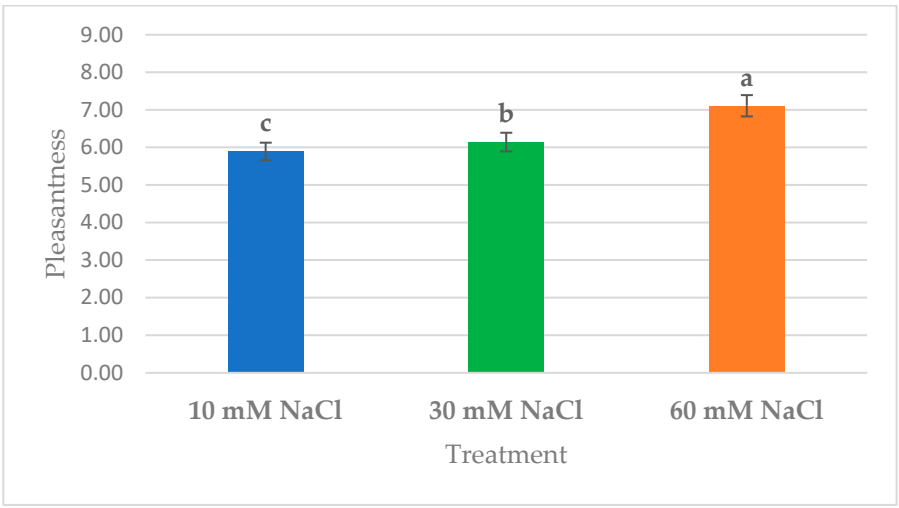


Figure 4. Overall hedonic indexes of pleasantness attributed by panellists for tomato fruits grown with different salt concentrations of nutrient solution: 10 mM, 30 mM, and 60 mM of NaCl. Mean values ($n = 10$) ± standard deviation followed by different letters are statistically different ($p < 0.05$) according to the LSD test.

The quality of vegetables and fruits is defined by a number of indirect factors, such as chemical composition, the presence of bioactive compounds, the absence of agrochemicals and anti-nutrients, as well as those that are directly perceived, such as taste and aroma, which typically define physical quality and determine consumers' acceptance and the retail price of the final product [66,67].

A Hierarchical Cluster Analysis (HCA) was conducted on the complete set of biometric and sensorial data, revealing an initial classification of the samples into two primary groups, as shown in the two-way dendrogram in Figure 5.

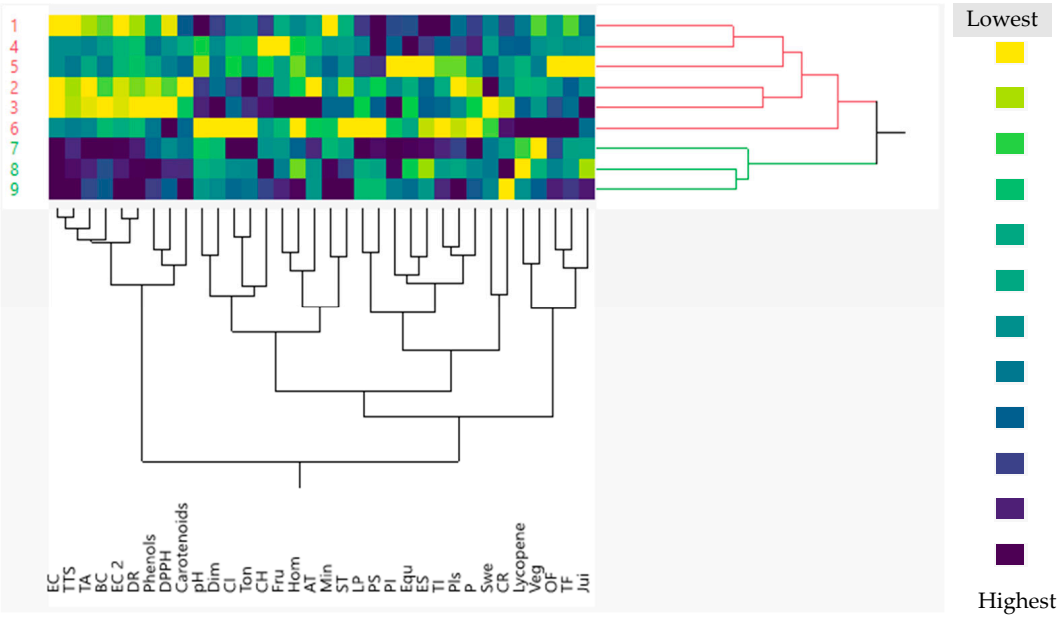


Figure 5. Two-way dendrogram of Hierarchical Cluster Analysis (HCA) on integrated biometric and sensorial data of tomato fruits grown with 10 mM of NaCl (1–3), tomato fruits grown with 30 mM of NaCl (4–6), and tomato fruits grown with 60 mM of NaCl (7–9), including Color Intensity (CI), Tonality (Ton), Color Homogeneity (CH), Dimensions (Dim), Presence of Lacerations (LP), Olfactory Frankness (OF), Perfume Intensity (PI), Vegetal (Veg), Fruity (Fru), Mineral (Min), Taste Frankness (TF), Taste Intensity (TI), Acidity (AT), Sapidity (ST), Sweetness (Swe), Chewing Resistance (CR), Juiciness (Jui), Homogeneity (Hom), Presence of Seeds (PS), Evolutionary State (ES), Pleasantness (Pls), Titratable Acidity (TA), Persistence (P), Total Soluble Solids (TTS: °Brix), Equilibrium (Equ), Dry matter (DR), Electrical Conductivity of nutritive solution (EC: dS m^{-1}), and Electrical Conductivity of tomato juice (EC2: dS m^{-1}).

The first cluster (red) encompassed both tomato fruit samples grown with 10 mM and 30 mM of NaCl, whereas the second cluster (green) consisted of three replicates of treated samples with the highest salinity (60 mM of NaCl). Notably, within the red cluster, the samples grown with 10 mM NaCl were closer to those treated with 30 mM NaCl, compared to those treated with the highest sodium chloride concentration (60 mM). The clustering of the studied parameters emphasised the influence of biometric parameters, forming a distinct cluster, except for the pH and lycopene versus sensorial parameters.

The Principal Component Analysis (PCA), illustrated in Figure 6, revealed a total correlation exceeding 54% (PC1:28.7%, PC2:26.2%).

The PCA effectively discriminated control samples from treated ones, positioning them on the left side of the plot (PC1 < 0), while the treated samples were dispersed throughout the right quadrants (PC1 > 0). Samples treated with higher salinity predominantly occupied the upper quadrant (PC2 > 0), with one exception (8), while those treated with 30 mM of NaCl were positioned in the lower quadrant (PC2 < 0).

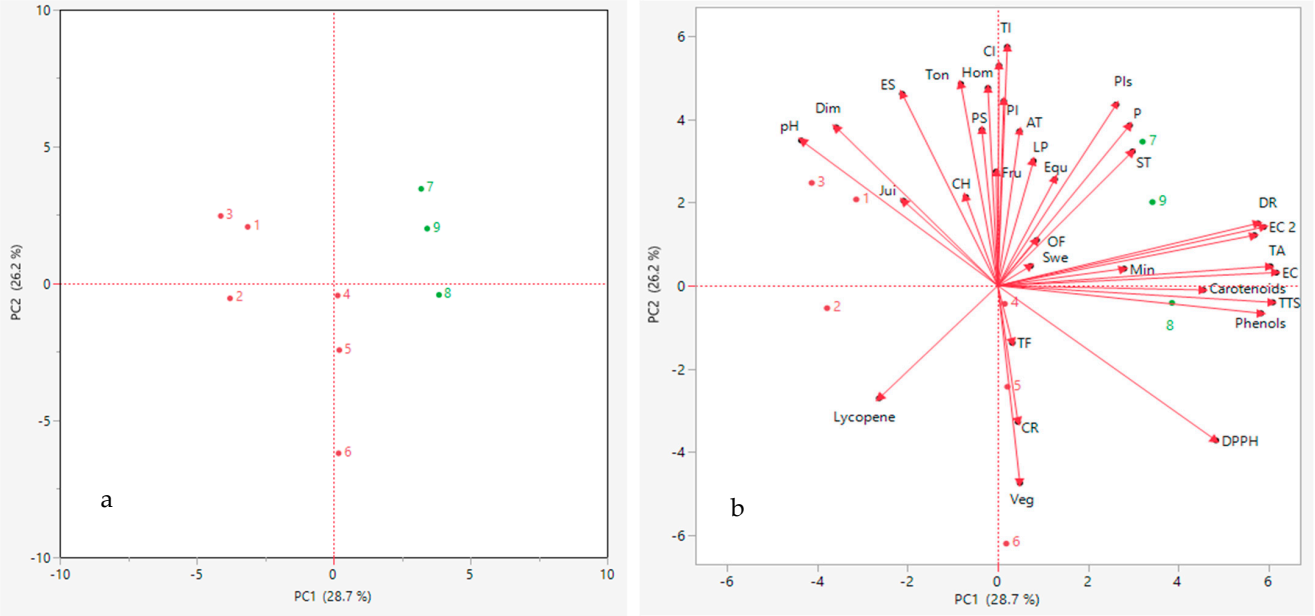


Figure 6. Principal Component Analysis (PCA) score plot (**a**) and biplot (**b**) of integrated biometric and sensorial data of tomato fruits grown with 10 mM of NaCl (1–3), tomato fruits grown with 30 mM of NaCl (4–6), and tomato fruits grown with 60 mM of NaCl (7–9), including Color Intensity (CI), Tonality (Ton), Color Homogeneity (CH), Dimensions (Dim), Presence of Lacerations (LP), Olfactory Frankness (OF), Perfume Intensity (PI), Vegetal (Veg), Fruity (Fru), Mineral (Min), Taste Frankness (TF), Taste Intensity (TI), Acidity (AT), Sapidity (ST), Sweetness (Swe), Chewing Resistance (CR), Juiciness (Jui), Homogeneity (Hom), Presence of Seeds (PS), Evolutionary State (ES), Pleasantness (Pls), Titratable Acidity (TA), Persistence (P), Total Soluble Solids (TTS: °Brix), Equilibrium (Equ), Dry matter (DR), Electrical Conductivity of nutritive solution (EC: dS m^{-1}), and Electrical Conductivity of tomato juice (EC2: dS m^{-1}).

It is noteworthy that nearly all sensorial and biometric parameters exhibited intermediate values between the fruits grown with 10 mM and 30 mM of NaCl, except for lycopene, Chewing Resistance (CR), Vegetal characteristics, Taste Frankness (TF), and DPPH, which displayed elevated levels in tomato fruits grown with 10 mM and 30 mM of sodium chloride.

Most sensorial and biometric parameters exhibited intermediate values between the samples grown with 10 mM and 60 mM of NaCl except for lycopene, chewing resistance (CR), Vegetal characteristics, Taste Frankness (TF), and DPPH, which displayed elevated levels in the fruits grown with 10 mM and 30 mM of NaCl. The sensory analysis and investigation of healthy properties in tomatoes grown soilless under salt stress conditions highlight the potential for cultivating superior quality tomatoes. This approach may enable local farmers to command higher prices for their product, compensating for yield reductions caused by salt stress [16,20,24,68]. These findings underscore the viability of this strategy for tomato cultivation, aligning with previous research reports [16,20,24,68].

4. Conclusions

Irrigation with saline water presents challenges for tomato growers, especially in the Mediterranean region, where high salt levels in soil or irrigation water are common. However, proper management and the use of salt-tolerant landrace tomato cultivars can mitigate these effects and even reap some potential benefits.

This study demonstrated that while salinity can reduce yield, it can also enhance fruit quality by improving the organoleptic parameters and nutraceutical compounds. This highlights the importance of a balanced approach considering both quality and yield in tomatoes cultivated under saline conditions. Sensory analysis favoured tomatoes grown

under high salinity, suggesting potential benefits for 'Pisanello' tomatoes. Further research could optimise salinity levels to maximise tomato yield and enhance fruit quality enriched with nutraceutical compounds.

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