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Assessing Salinity Tolerance and Fruit Quality of Pepper Landraces

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Abstract: Soil salinity caused by climate change is a major global issue, especially in regions like the Mediterranean basin. Most commercially cultivated horticultural species, including pepper, are considered to be salt sensitive. However, some underutilized genotypes exhibit high adaptability to adverse environmental conditions, without compromising yield. This study aimed to investigate the effects of salinity stress on the yield, nutrition, and fruit quality of four pepper landraces: JO 109 (*Capsicum annuum* var. *grossum*), JO 204 (*Capsicum annuum* var. *grossum*), JO 207 (*Capsicum annuum* var. *grossum*), and 'Florinis'. The California cultivar 'Yolo Wonder' and the commercial F_1 hybrid 'Sammy RZ' were used as controls. The experiment was conducted in the greenhouse facilities of the Laboratory of Vegetable Production at the Agricultural University of Athens. Half of the plants were exposed to a nutrient solution containing NaCl at a concentration that could maintain the NaCl level in the rhizosphere at 30 mM (salt-treated plants), while the remaining plants were irrigated with a nutrient solution containing 0.5 mM NaCl (control plants). Yield and yield quality attributes, such as firmness, titratable acidity (TA), total soluble solids content (TSSC), fruit height, and diameter were recorded. The results revealed that the landraces were more tolerant to salinity than the commercial varieties 'Yolo Wonder' and 'Sammy RZ'. Moreover, subjecting pepper plants to increased salinity resulted in increased fruit quality, manifested by an increase in TSSC and TA.

Keywords: soilless culture; *Capsicum annuum*; abiotic stress; yield; organoleptic value; nutrient concentration

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1. Introduction

Salinity refers to the increased salt content in soil or growing media [1], which creates a challenging growth environment for plant growth resulting in reduced yield and product quality [2]. This is ascribed to the disturbance in the balance of water uptake by plant roots, leading to osmotic stress conditions [3,4]. A consequent effect of this imbalance, besides the restriction of water uptake by root cells, is the reduced absorbance of essential nutrients by the roots, which results in deficiencies [5].

In addition to its detrimental effects, under low concentrations, salinity can positively impact crop performance [6] through the eustress phenomenon [7]. Controlled exposure to moderate levels of salinity has proven beneficial for fruit quality [8] by improving some organoleptic characteristics of the fruit such as firmness, the Total Soluble Solids Content (TSSC °Brix) [9], and titratable acidity [10].

Salinity is an abiotic factor that can cause nutritional and metabolic imbalances, resulting in a complex physiological syndrome [11]. However, a key mechanism that determines a plant's tolerance to salinity is the control of ion homeostasis, particularly in terms of K and Na [12]. Additionally, a high K^+/Na^+ ratio in leaves of traditional plant cultivars has been linked to salinity tolerance [13], whereas contrasting significant increases in the Na^+/K^+ ratio have been observed in roots of highly sensitive alfalfa plants, suggesting a reduced ability to inhibit Na+ absorption and uphold ion balance [14]. Metabolomic studies of plants exposed to salinity stress have identified several metabolites such as amino acids (AAs), sugars, polyols, and other Krebs cycle intermediates that are associated with salinity stress [15]. These metabolites act as biochemical targets under such conditions [16,17].

Pepper is cultivated worldwide due to the wide variety in the shape, size, and color of fruits [18]. They are primarily valued for their taste, nutritional benefits, and their contribution to a healthy human diet [19]. Pepper (*Capsicum annuum* L.) is a plant species highly sensitive to salinity, resulting in a yield decrease of approximately 7.6% for each unit increase in EC beyond 2.8 dS m^{-1} in the root environment [20]. Despite this sensitivity, fruit quality can be significantly enhanced by controlled elevation of EC above the threshold required for maximum yield. Several authors have described the relationship between salinity and crop yield, which decreases as salinity increases [21–23]. Therefore, the recommended electrical conductivity (EC) range for the root environment of soilless cultivated pepper is between 3 and 3.6 dS m^{-1} [24]. However, there are landraces that exhibit salinity tolerance and could serve as an important genetic resource for breeding programs [25].

The aim of the present study was to evaluate the salinity tolerance of different pepper landraces originating or cultivated in the Mediterranean area, by assessing their productivity, fruit quality characteristics, and leaf and fruit nutritional status. A comprehensive analysis of the results will provide evidence of the parameters that confer salinity stress tolerance in pepper plants. The obtained knowledge can be utilized in breeding programs aiming to create (a) new varieties or hybrids that can be cultivated in harsh saline environments without the risk of yield compromise, or (b) new rootstocks for the production of grafted plants.

2. Materials and Methods

2.1. Biological Material and Experimental Design

The experiment was conducted in the greenhouse facilities (37°59′2″ N, 23°42′19″ E) of the Laboratory of Vegetable Production at the Agricultural University of Athens (AUA). Three landraces from Jordan, a Greek landrace, the "Yolo Wonder" variety as a reference, and the "Sammy RZ" hybrid also employed as a reference were cultivated in an open soilless culture system, with two distinct concentrations of NaCl (0.5 and 30 mM) applied to the nutrient solution within the root zone (root solution). In Table 1, details on the names and origins of the pepper seeds utilized in this experiment are given. The experimental design followed a randomized complete block design (RCBD).

Table 1. The origins and names of the pepper seeds used in the experiment.

Variety	Provider	Material Type
Yolo Wonder	INRA [1]	Commercial—Reference
JO 109 (*Capsicum annuum* var. *grossum*)	NARC [2]	Jordanian landrace
JO 204 (*Capsicum annuum* var. *grossum*)	NARC [2]	Jordanian landrace
JO 207 (*Capsicum annuum* var. *grossum*)	NARC [2]	Jordanian landrace
Florinis	AUA [3]	Greek landrace
Sammy RZ (F1 Hybrid)	Rijk Zwaan [4]	Commercial hybrid—Reference

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2.2. Growing the Seedlings

To ensure the viability of the initial material, prior to sowing, on 20 September 2021 all seeds underwent an initial disinfection process. This process involved soaking the seeds of each variety in a 15% v/w solution of Na_3PO_4 for 20 min. Following disinfection, seeds were placed in Petri dishes and incubated in a temperature-controlled chamber at 25 °C for 5 days. By 27 September 2021, the germinated seeds were transferred to sowing trays, allowing seedlings to grow in a turf substrate.

2.3. Cultivation Practice

On 13 November 2021, seedlings reaching the stage of 4–5 true leaves were transplanted into 33 L perlite bags in an open hydroponic system. Salinity stress was imposed at this stage as the salinized plants received a concentration of 30 mM NaCl in the nutrient solution, while the control plants were supplied with 0.5 mM NaCl. The perlite bags were soaked in the nutrient solution (NS) (see Starter Solution, Table 2) for 24 h, while to facilitate adequate drainage of excess nutrient solution, cuts were made at the bottom of each bag. Subsequently, both control and salinized plants were regularly supplied with an NS (germination solution) containing the proper amount of NaCl (0.5 and 30 mM, respectively). Each treatment was quadrupled, with one perlite bag per treatment replication. Each perlite bag accommodated three plants of the same cultivar grown and supplied with an NS through a drip irrigation system with a flow rate of 2 L h^{-1}. Throughout the growing season, a heating system maintained the mean day and night temperatures at 21 °C and 17 °C, respectively.

Table 2. The nutrient concentrations in the starter solution and within the nutrient solution supplied to the pepper plants throughout the vegetative (VGS) and reproductive (RGS) growth stages.

Nutrient	Starter Solution (13 November 2021)	VGS (14 November 2021)	RGS (7 February 2022)	Unit
NO^{3-}	16.05	15.79	16.64	mM
K^+	5.70	5.86	6.94	mM
Ca^{2+}	6.15	5.60	5.55	mM
Mg^{2+}	2.50	1.63	1.66	mM
$SO_4{}^{2-}$	3.27	2.10	2.08	mM
$H_2PO_4{}^-$	1.25	1.35	1.35	mM
$NH_4{}^+$	1.05	1.22	1.00	mM
Fe	20.00	20.00	16.20	µM
Mn^{++}	12.00	12.00	10.80	µM
Zn^{++}	7.00	6.00	5.40	µM
B	50.00	32.00	32.40	µM
Cu^{++}	0.80	0.80	0.86	µM
Mo	0.60	0.60	0.54	µM
Cl^-	0.40	0.40	0.40	µM

2.4. Nutrient Solution Formula

To ensure that the plants received the necessary macro- and micronutrients crucial for their optimal growth at each stage, they were irrigated using appropriate nutrient solutions. The calculation of the nutrient solution (NS) for pepper plants involved utilizing the NUTRISENSE decision support system, accessible at https://nutrisense.online (accessed on 16 January 2024) [26]. Initially, concentrated solutions were prepared and diluted at a 1:100 ratio to create the NS distributed to the plants. Half of the plants were provided with an NS containing the proper amount of NaCl to establish a concentration of 30 mM (salinity treatment) in the rhizosphere, while the other half received an NS containing 0.5 mM NaCl, identical to the irrigation water (control treatment). A daily pH adjustment of the NS to 5.6 took place using the appropriate amount of a 1 N HNO_3 solution. Throughout the experiment, three formulations were employed, tailored to the specific growth stages (starter, vegetative, and reproductive growth stage, respectively). Detailed concentrations of both macro- and micronutrients for each treatment and growth stage are outlined in Table 2.

2.5. Salt Stress Application in Open-Loop Soilless Systems

To impose salt stress, a specific procedure was followed:

1. A 30 mmol L^{-1} NS with an electrical conductivity (EC) of 6 dS m^{-1} was prepared to be used as the starter by including, as well, the NaCl of the irrigation water (see Table 2). This solution was applied to moisten perlite up to saturation. Subsequently, measures were taken to enable free drainage, thereby allowing perlite's moisture status reduction to container capacity.
2. The NaCl concentration in the NS supplied to the plants after transplanting (C_t) was calculated using Equation (1).

$$C_t = \alpha\, C_d + (1 - \alpha)\, C_u \quad (1)$$

The value used for the target drainage fraction (a) in (1) normally ranges from 0.1 to 0.35. Furthermore, C_d in (1) was replaced by the target NaCl concentration in the root zone (i.e., 30 mmol L^{-1}).

To calculate the uptake Na^+ concentration (C_u) in (1), the relationship suggested by Savvas et al., 2008 [27] for pepper was used:

$$C_u = 0.0252\, C_r^{1.441} \quad (2)$$

Using Equation (2), the actual Na^+ UC (C_u) in pepper crops can be calculated based on the actual concentration of Na^+ in the root environment (C_r). By substituting C_r with 30 mmol L^{-1} (the target concentration of Na^+ within the pepper's root zone) in (2), C_u of 3.4 mmol L^{-1} is achieved. Moreover, the replacement of C_u with 3.4 mmol L^{-1} in (1), and a with the standard drainage fraction of 0.3, generates a C_t of 11.4 mmol L^{-1}.

3. A standard NS of 2.2 dS m^{-1} EC proper for pepper cultivation in open-loop soilless systems was prepared following the addition of fertilizers [24]. Subsequently, NaCl was added, at a concentration of 11.4 mmol L^{-1}, increasing the EC by 1.3 dS m^{-1}. Thus, the pepper plants were supplied with an NS of 3.5 dS m^{-1} after transplanting.
4. On a weekly basis, the sodium concentration in the drainage solution was observed to adjust the level of NaCl accordingly. If the recorded Na concentration significantly differed from 30 mmol L^{-1}, Cu was calculated using Equation (3).

$$C_u = [2dV_s\, C_t - 2V_r\, (C_{ra} - C_{rp}) - d\alpha V_s\, (C_{ra} + C_{rp})]/2d\, (1 - \alpha)\, V_s) \quad (3)$$

where α is the applied drainage fraction, C_t is the current Na^+ concentration in NS, V_s is the daily volume of NS (L $plant^{-1}$), d is the number of days since the last Na^+ measurement in the root zone, C_{ra} is the current concentration of Na^+ in the root zone, C_{rp} is the previous concentration of Na^+ in the root zone, and V_r is the volume of Ns in the root zone of the crop (L $plant^{-1}$).

2.6. Leaf and Fruit Sampling for Macro- and Micronutrient Analysis

Upon completion of the experiment, pepper plants of each treatment were sampled. The 3rd, 4th, and 5th leaves from the top of every plant were sampled for the determination of the nutrient profiles of the pepper plants. In addition, fruits were also sampled during harvest and their fresh weight was recorded. Both leaves and fruits were then dried at 65 °C to a constant weight.

2.7. Yield Measurement

The initial fruit harvest occurred approximately 14 to 15 weeks after transplanting the plants into the greenhouse. Subsequent harvests were conducted at intervals of once or twice a week until the experiment's termination, each time reaching the commercially acceptable fruit maturity stage. Parameters such as the total number of fruits per plant, their total fresh weight (g plant^{-1}), and the average fresh weight (g) were recorded.

2.8. Nutrient Analysis

Following drying, all samples were milled using an MF 10 Basic Micro Fine Grinder (IKA Werke, Staufen, Germany). Sample extraction was carried out using the dry ashing method. Potassium (K) and sodium (Na) were measured in this extract using a flame photometer (Sherwood Model 410, Cambridge, UK). Calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) concentrations were measured with the use of an atomic absorption spectrophotometer (AA-7000, Shimadzu Co., Tokyo, Japan).

2.9. Quality Characteristics

Quality parameters such as the fruit diameter, fruit length, the titratable acidity, and the firmness of ten ripe fruits per treatment were recorded. Fruit acidity (FA) was determined in 10 mL of juice through potentiometric titration with 0.02 M NaOH to pH 8.1. Fruit firmness was measured using a Mechanical Force Gauge (Chatillon penetrometer-DPP5KG). Total Soluble Solids Content (TSSC °Brix) (TSSC) was determined using a refractometer (Schmidt & Haensch HR32B, Berlin, Germany).

2.10. Statistical Analysis

In the current study, the yield parameters underwent one-way ANOVA, whereas two-way ANOVA was employed to study the responses of the pepper genotypes, in terms of fruit quality and plant mineral profile, to salinity stress. The statistical evaluation was performed using the STATISTICA software package, version 12.0 for Windows. If the salinity stress and/or genotype demonstrated a significant influence on a measured parameter, Duncan's multiple range test ($p \leq 5\%$) was also employed to differentiate means within each factor.

3. Results

Figure 1 illustrates the yield of each variety either grown under normal conditions or subjected to salinity stress. The commercial varieties 'Yolo Wonder' and 'Sammy,' used as reference cultivars, exhibited the highest average fruit weight per plant under control conditions. However, upon the addition of NaCl to the nutrient solution, a statistically significant reduction in fruit weight per plant was observed. Specifically, for 'Yolo Wonder' a decrease of approximately 29% was recorded, while for 'Sammy' the decrease was 27%. Moreover, a decline in yield was evident in the landrace 'Florinis'. Conversely, the Jordanian Landraces 'JO 109', 'JO 204', and 'JO 207' demonstrated no significant reduction in yield under stress conditions.

In Table 3 the number of fruit for each variety, along with their respective mean weights, is given. Specifically, the varieties 'Yolo Wonder', 'Sammy', and 'Florinis' exhibited reduced yield under saline conditions. This reduction stemmed from a decrease in the number of fruit per plant with the addition of 30 mM NaCl to the nutrient solution. However, it is noteworthy that, despite this decrease in fruit number, no significant reduction in fruit weight was evident.

Under saline stress conditions, the diameter and length of pepper fruits decreased by 13% and 9%, respectively (Table 4). Additionally, the tested cultivars exhibited variable responses for these parameters, with the reference cultivar 'Yolo Wonder' showcasing the largest diameter, and the 'Sammy RZ' hybrid displaying the longest fruit length. Regarding the interaction between the two factors (salinity and cultivar), even though no significant difference was noted for diameter, fruit length was significantly affected by the treatments applied. Specifically, a reduction in fruit length was found only for 'JO 204′, 'JO 207′, and 'Florinis', which were reduced by 11%, 19%, and 21%, respectively.

Table 3. Impact of salinity stress (30 mM NaCl) on the mean fruit number per plant (FN) and the mean fruit weight (MFW) of the evaluated genotypes.

	FN (No Plant^{-1})						MFW (g)					
Salinity Stress	**Yolo Wonder**	**JO109**	**JO204**	**JO207**	**Florinis**	**Sammy RZ**	**Yolo Wonder**	**JO109**	**JO204**	**JO207**	**Florinis**	**Sammy RZ**
0.5 mM NaCl	5.83 a	28.58	25.08	17.67	7.58 a	15.83 a	123.39	14.72	10.17	13.48	52.47	59.58
30 mM NaCl	4.50 b	28.58	20.00	21.50	3.58 b	11.00 b	113.03	14.24	9.30	12.10	51.00	62.42
Statistical significance	*	NS	NS	NS	***	**	NS	NS	NS	NS	NS	NS

Mean values (n = 4) marked with distinct letters within the same column indicate significant differences as determined by Duncan's multiple range test ($p < 0.05$). *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.05$) denote statistical significance. NS denotes non-significance.

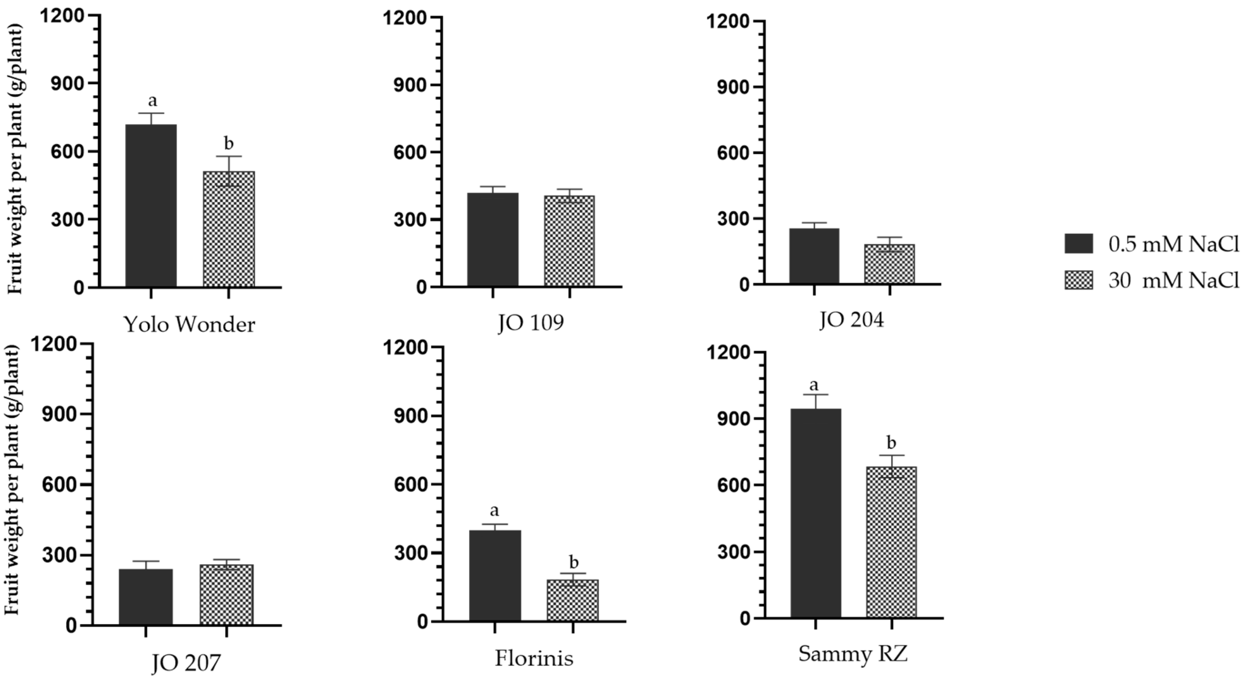

Figure 1. Impact of salinity stress on fruit weight per plant (g/plant) for each pepper genotype. In the figure, the entry labeled '0.5 mM NaCl' denotes the control conditions, indicating the absence of added NaCl. On the other hand, '30 mM NaCl' is indicative of exposure to salinity stress. For each treatment, the different letters in each bar indicate significant differences according to Duncan's multiple range test ($p < 0.05$). Vertical bars indicate the standard errors of means (n = 4).

Table 4. Impact of salinity stress (30 mM NaCl) on pepper fruit length and diameter.

Salinity Stress	Variety	Fruit Diameter (mm)	Fruit Length (mm)
	Main effects (Salinity stress)		
0.5 mM NaCl		37.82 a	107.40 a
30 mM NaCl		32.95 b	97.57 b
	Main effects (Variety)		
	Yolo Wonder	76.58 a	67.82 d
	JO 109	34.11 c	69.73 d
	JO 204	10.76 e	117.82 b
	JO 207	21.97 d	109.13 c
	Florinis	42.64 b	103.01 c
	Sammy RZ (F1 Hybrid)	42.61 b	143.35 a

Table 4. *Cont.*

Salinity Stress	Variety	Fruit Diameter (mm)	Fruit Length (mm)
Interaction			
0.5 mM NaCl	Yolo Wonder	67.41	67.41 e
	JO 109	73.45	73.45 e
	JO 204	124.69	124.69 b
	JO 207	120.72	120.72 bc
	Florinis	112.67	112.67 c
	Sammy RZ (F1 Hybrid)	148.40	148.40 a
30 mM NaCl	Yolo Wonder	68.75	68.75 e
	JO 109	67.50	67.50 e
	JO 204	110.95	110.95 c
	JO 207	97.55	97.55 d
	Florinis	89.22	89.22 d
	Sammy RZ (F1 Hybrid)	140.20	140.20 a
Statistical significance			
Salinity stress		*	***
Variety		***	***
Salinity stress × Variety		NS	**

Mean values (n = 10) marked with distinct letters within the same column indicate significant differences as determined by Duncan's multiple range test ($p < 0.05$). *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.05$) denote statistical significance. NS denotes non-significance.

The salt stress notably impacted the citric acid content and TSSC in the fruits, elevating them by approximately 9% and 5%, respectively, compared to peppers cultivated under control conditions (Table 5). The cultivar type significantly influenced the TSSC and acidity and consistency parameters, wherein the 'Sammy RZ' hybrid exhibited the lowest TSSC and titratable acidity, while the reference variety 'Yolo Wonder' displayed the highest fruit firmness.

Table 5. Impact of salinity stress (30 mM NaCl) on mean total soluble solids content (TSSC), titratable acidity (FA), and firmness (FF) of fruit of different genotypes.

Salinity Stress	Variety	TSSC (°Brix)	TA (g Citric Acid per 100 g Juice)	FF (Kg)
Main effects (Salinity stress)				
0.5 mM NaCl		5.10 b	0.11 b	2.01
30 mM NaCl		5.33 a	0.12 a	1.88
Main effects (Variety)				
	Yolo Wonder	4.14 c	0.10 bc	3.04 a
	JO 109	5.13 b	0.14 a	0.98 e
	JO 204	5.00 b	0.14 a	2.00 c
	JO 207	5.06 b	0.11 b	1.61 d
	Florinis	7.57 a	0.14 a	2.65 b
	Sammy RZ (F1 Hybrid)	3.63 d	0.08 c	2.00 c
Statistical significance				
Salinity stress		***	***	NS
Variety		***	***	***
Salinity stress × Variety		NS	NS	NS

Mean values (n = 10) marked with distinct letters within the same column indicate significant differences as determined by Duncan's multiple range test ($p < 0.05$). *** denotes statistical significance at $p < 0.001$. NS denotes non-significance.

Table 6 displays the concentrations of macronutrients such as K, Na, Ca, and Mg, along with the K/Na ratio in pepper plant leaves. The impact of salinity on these factors was analyzed, revealing notable differences among the treatments applied. In terms of K concentration in the leaves, a reduction of approximately 7% was found when plants were subjected to salinity stress. Additionally, the K/Na exhibited a significant decrease of about 30% under salinity stress conditions. Conversely, Na concentration in the leaves showed an increase of 38% when plants were exposed to saline stress. Notably, Ca concentrations did not display a statistically significant difference under stress conditions compared to those in normal growth conditions.

Table 6. Impact of salinity stress (30 mM NaCl) on the macronutrient concentration (K, Na, Ca, Mg, and K/Na) in the leaves of the evaluated genotypes.

Leaves						
Salinity Stress	**Variety**	**K (mg/g)**	**K/Na**	**Na (mg/g)**	**Ca (mg/g)**	**Mg (mg/g)**
Main effects (Salinity stress)						
0.5 mM NaCl		50.00 a	89.70 a	0.58 b	32.99	8.43 b
30 mM NaCl		46.60 b	64.42 b	0.80 a	34.54	9.32 a
Main effects (Variety)						
	Yolo Wonder	47.75 bc	75.55 ab	0.67	38.46 ab	10.26 a
	JO 109	57.86 a	94.34 a	0.68	27.33 d	8.89 b
	JO 204	43.43 c	62.77 b	0.72	26.31 d	7.67 c
	JO 207	50.71 b	86.35 a	0.60	33.01 c	9.42 b
	Florinis	42.57 c	74.64 ab	0.66	41.28 a	7.64 c
	Sammy RZ (F1 Hybrid)	48.29 bc	74.34 ab	0.76	35.18 bc	8.96 b
Interaction						
0.5 mM NaCl	Yolo Wonder	51.00	88.46 bc	0.59	34.97	10.24 a
	JO 109	65.67	131.64 a	0.50	28.26	7.91 cde
	JO 204	43.25	71.69 b–e	0.62	25.58	7.94 cde
	JO 207	51.50	89.92 bc	0.58	31.97	8.72 bc
	Florinis	43.75	95.90 b	0.49	41.47	7.14 e
	Sammy RZ (F1 Hybrid)	48.75	71.08 b–e	0.69	34.48	8.47 bcd
30 mM NaCl	Yolo Wonder	44.50	62.63 c–e	0.75	41.95	10.29 a
	JO 109	52.00	66.37 b–e	0.81	26.63	9.62 ab
	JO 204	43.67	50.87 de	0.85	27.28	7.32 de
	JO 207	49.67	81.60 b–d	0.63	34.41	10.36 a
	Florinis	41.00	46.30 e	0.89	41.03	8.29 cde
	Sammy RZ (F1 Hybrid)	47.67	78.69 b–e	0.86	36.11	9.61 ab
Statistical significance						
Salinity stress		*	***	***	NS	***
Variety		***	*	NS	***	***
Salinity stress × Variety		NS	*	NS	NS	*

Mean values (n = 4) marked with distinct letters within the same column indicate significant differences as determined by Duncan's multiple range test ($p < 0.05$). *** ($p < 0.001$)), and * ($p < 0.05$) denote statistical significance. NS denotes non-significance.

Regarding the studied variety factor, significant differences were noted in the concentrations of all the macronutrients assessed, except for Na since, across the various varieties, Na concentrations in the leaves remained consistently similar. In terms of K concentration in the leaves, among the cultivars, 'JO 109 (Capsicum annuum var. grossum)' exhibited higher levels compared to the other varieties. Moreover, 'Florinis' displayed the highest leaf Ca concentrations followed by the reference variety, 'Yolo Wonder'.

Salinity stress significantly decreased K/Na in the fruit of 'JO 109' and 'Florinis' pepper plants, while for all the other cultivars no significance response was recorded during the salinity treatments (0.5 and 30 mM, respectively). Moreover, by increasing the NaCl to 30 mM, a significant increase in the Mg content in leaves of 'JO 109' and 'JO 207' was detected, elevating it by approximately 22% and 19%, respectively, compared to those cultivated under control conditions. For all the other cultivars, no significant response to the 0.5 mM and 30 mM NaCl in the nutrient solution was detected.

The impact of salinity on the nutritional composition of fruit is obvious (Table 7). The concentration of Na in fruits increased by 80% with the addition of NaCl to the nutrient solution. However, the effect of NaCl extends beyond Na, with an 18% reduction in Ca and 5% in Mg concentrations in the fruit.

Table 7. Impact of salinity stress (30 mM NaCl) on the concentration of macronutrients (K, Na, Ca, Mg, and K/Na) in fruits of the evaluated genotypes.

		Fruit				
Salinity Stress	**Variety**	**K (mg/g)**	**K/Na**	**Na (mg/g)**	**Ca (mg/g)**	**Mg (mg/g)**
Main effects (Salinity stress)						
0.5 mM NaCl		30.09	178.04 a	0.18 b	0.11 a	1.41 a
30 mM NaCl		29.52	118.73 b	0.33 a	0.09 b	1.34 b
Main effects (Variety)						
	Yolo Wonder	28.57 b	100.26 d	0.45 a	0.07 b	1.39 a
	JO 109	31.75 a	187.61 ab	0.18 c	0.09 b	1.48 a
	JO 204	31.14 a	130.16 c	0.25 b	0.13 a	1.47 a
	JO 207	32.00 a	201.80 a	0.17 c	0.13 a	1.48 a
	Florinis	22.57 c	94.63 d	0.29 b	0.08 b	0.96 b
	Sammy RZ (F1 Hybrid)	32.25 a	165.21 b	0.21 b	0.09 b	1.43 a
Interaction						
0.5 mM NaCl	Yolo Wonder	29.50	155.39 bc	0.20 de	0.07	1.43
	JO 109	31.50	216.83 a	0.15 e	0.12	1.58
	JO 204	30.50	147.76 bcd	0.22 de	0.12	1.50
	JO 207	34.00	214.75 a	0.17 e	0.15	1.54
	Florinis	22.50	125.21 cd	0.18 e	0.10	0.97
	Sammy RZ (F1 Hybrid)	33.50	211.86 a	0.16 e	0.09	1.44
30 mM NaCl	Yolo Wonder	27.33	45.14 e	0.63 a	0.07	1.36
	JO 109	32.00	158.40 bc	0.21 de	0.06	1.38
	JO 204	32.00	106.69 d	0.30 c	0.13	1.42
	JO 207	30.50	192.09 ab	0.17 e	0.12	1.42
	Florinis	22.67	53.85 e	0.43 b	0.05	0.96
	Sammy RZ (F1 Hybrid)	31.00	118.57 cd	0.27 cd	0.08	1.41
Statistical significance						
Salinity stress		NS	***	***	**	***
Variety		***	***	***	***	***
Salinity stress × Variety		NS	*	***	NS	NS

Mean values (n = 4) marked with distinct letters within the same column indicate significant differences as determined by Duncan's multiple range test ($p < 0.05$). *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.05$) denote statistical significance. NS denotes non-significance.

The effect of variety proved to be particularly significant in all measured macronutrients. In particular, in terms of Na concentration, the reference variety 'Yolo Wonder' showed the highest levels, while having the lowest K/Na. In contrast, the landrace 'JO 207' showed the lowest Na concentration in fruit while having the highest levels of all other macronutrients measured, including K/Na, compared to the other varieties studied.

When analyzing the interaction between salinity stress and the different cultivars grown, a statistically significant variation in fruit Na concentration and K/Na was found. In particular, the reference genotypes 'Yolo Wonder' and 'Sammy RZ' and the landrace 'Florins', which showed reduced yields under salinity stress, also showed a remarkable statistical difference in Na concentration and K/Na between the two treatments.

4. Discussion

It is well documented that salinity is an abiotic stressor capable of reducing crop growth and productivity by affecting the ability of plants to absorb water and nutrients [28,29]. In the present study, we aimed to assess the impact of salinity on six pepper cultivars, by evaluating fruit yield under moderate NaCl concentration (30 mM) in the root zone. The results revealed a significant reduction of yield under salinity stress for the commercial cultivars 'Yolo Wonder' and 'Sammy', as well as the landrace 'Florinis'. In a study conducted by ALKahtani and colleagues [30], it was found that under salinity conditions of 34 mM, the yield of 'Yolo Wonder' decreased as the number of fruits per plant decreased. Furthermore, Giorio et al. [31] reported a 36% reduction in an Italian landrace at 30 mM compared to the control treatment. The same reduction was also observed in the Greek landrace 'Florinis'. However, in our study, the reduction in fruit yield was ascribed to the decreased fruit number, rather than the decreased average fruit weight. This observation aligns well with the results of Veloso et al. [32] on the reduction in the number of pepper fruits associated with increasing EC. Giuffrida et al. [10] highlighted that high salinity levels can lead to fruit drop due to physiological and biochemical changes induced by high salt concentration, which directly affects the fruit number. The landraces 'JO 109′, 'JO 204′, and 'JO 207′ from Jordan were the only ones that maintained a stable yield unaffected by the addition of NaCl to the nutrient solution. This suggests that tolerance to salt stress is a cultivar-dependent characteristic [33].

Regarding fruit quality characteristics, salinity stress resulted in a 13% decrease in fruit diameter and 9% in fruit length, which is in accordance with the previous reports [34,35]. According to Navarro et al. [36], this can be attributed to reduced water absorption and restricted accessibility to plant tissues caused by salinity, leading to metabolic changes within cells. In this study, NaCl (30 mM) in the root zone increased TSSC and TA by 5% and 9%, respectively. Similar TSSC and TA results were recorded by Qiu et al. [37] in hot peppers, and by Patil et al. [38] in bell peppers. The explanation probably lies in the reduced water accumulation [39] and the increased accumulation of Na, K, and Cl in fruits induced by salinity [40]. Interestingly, in this study no significant impact on fruit firmness was found in pepper plants subjected to salinity stress, in line with the results of Salinas et al. [34]. This consistency may be linked to the absence of significant differences in the fruit Ca content between the two treatments for each cultivar, supporting the correlation between Ca content and firmness [41].

In the present study, the addition of NaCl to the nutrient solution significantly increased Na concentration in plant tissues. Similarly, Shiyab et al. [42] observed this phenomenon in hydroponic tomato cultivation when applying saline stress. However, in this study, the Na concentration in leaves of saline-treated plants increased by 38% and in fruits by 80% compared to the control, indicating that the Na accumulation rate is higher in fruits rather than in leaves. Similar findings have also been reported in the study of Azuma et al. [43]. Notably, in the present study, significant differences in fruit Na concentration were found among the different cultivars subjected to salinity stress. Among the tested varieties only two, the 'JO 109' and the 'JO 207' landraces, exhibited no significant difference in Na concentration in their fruits under stress conditions. Notably these landraces also did not show decreased yield when grown under stress conditions, suggesting a potential connection between Na accumulation in fruits and the overall resilience of certain pepper landraces to salinity stress.

According to Shabala and Cuin, [44], the transport and absorption of K and Na, and thus the K/Na ratio in plant tissues, are indicative of plants' tolerance to salinity. Genotypes with the ability to maintain high K/Na ratios in plant tissues are also characterized as salt tolerant [45]. In the present study, the landraces 'JO 109' and 'JO 207' exhibited a higher K/Na ratio in both leaves and fruit. Additionally, comparing the K/Na ratios between the two treatments for the different cultivars, it was observed that the landraces 'JO 204' and 'JO 207', as well as the two reference varieties 'Sammy' and 'Yolo Wonder', did not show a significant reduction in the K/Na ratio in their leaves. Similarly, the K/Na ratio in the fruit remained stable for the landraces 'JO 109' and 'JO 207'. In Qaryouti et al. [46]'s study, two of the varieties we cultivated, namely 'JO 204' and 'JO 207', were also investigated. On one hand, Qaryouti et al. [46] indicate that these landraces were among the least sensitive to salinity. On the other hand, they note that Jordanian landraces, including these two, have been irrigated for decades with low-quality water. This information supports the resilience of these landraces to the current salinity stress, evident in their highest K/Na ratio. This high ratio results from the consistent concentration of Na in the plant tissues of these landraces across both treatments. These landraces could also be characterized as tolerant to the applied moderate stress, since they managed to maintain the K/Na ratio without a reduction in yield.

Potassium (K) is an element that plays a crucial role in plants' responses to salinity stress, as high K/Na ratio levels are indicative of salinity tolerance [47]. However, competition between K and Na can lead to reduced K uptake due to decreased water uptake [48]. Here, a moderate salinity level (30 mM NaCl) in the root zone resulted in a significant decrease (approximately 7%) in leaf K concentration. However, there was no significant alteration in fruit K concentration due to salinity stress, in line with the results of Giuffrida et al. [10], for 18 mM of NaCl in the nutrient solution. Significant differences in K concentration were evident in both leaves and fruits among the tested cultivars as a result of the different K uptake and accumulation levels of these cultivars. However, the interaction between salinity and variety showed no significant effects on the aforementioned plant parts, consistent with the finding of Ntanasi et al. [1] for tomato landraces subjected to the same stress.

According to Yadav et al. [49], a decrease in Ca concentration in plants subjected to salinity stress, as a result of Na and Cl competition in plant tissues, can be found. The results of the present study indicate that salinity did not have a significant effect on the concentration of Ca in the leaves. Conversely, a significant reduction (approximately 18%) was observed in pepper fruit Ca concentration. Similarly, Giuffrida et al. [10] discovered no differences in leaf Ca concentration in pepper plants grown under NaCl salinity stress, while a 25% decrease was observed in their fruit. Regarding the different varieties, 'Yolo Wonder' and 'Florinis' exhibited the highest leaf Ca concentrations, while 'JO 204' and 'JO 207' showed the highest fruit Ca concentrations. The interaction between salinity and variety did not result in significant differences in the Ca concentration of either plant part. On the contrary, in a study on pepper cultivation in an NFT system, Lycoskoufis et al. [50] observed a small decrease in Ca concentration in the leaves when plants were irrigated with a nutrient solution of 60 mM NaCl, probably due to membrane integrity loss caused by the high level of salinity being applied. Therefore, the lack of significant differences between the Ca concentrations in leaves and fruits in this study may be attributed to the mild stress of 30 mM NaCl in the rhizosphere to which the pepper plants were subjected, which is not high enough to cause the above-mentioned physiological changes.

According to Ahmad et al. [51] and Yildirim et al. [52], high NaCl concentration in the nutrient solution may result in reduced Mg uptake by the plants. However, in the current study, the application of a moderate salinity stress (i.e., 30 mM NaCl) resulted in an approximately 10% increase in leaves' Mg concentration, while the reverse was the case in fruit, where a 5% decrease was noted. In accordance with these findings, Aktas et al. [53] found that salinity leads to an increase in Mg concentration in leaves and a decrease in fruit. As far as the cultivars are concerned, 'Yolo Wonder', the reference variety, exhibited the highest leaf Mg concentration, while 'Florinis' had the lowest fruit Mg concentration. The lack of significant interaction between the level of salinity and the tested varieties' Mg concentrations suggests that the impact of salinity did not vary significantly across different pepper varieties. This genotype-dependent characteristic of tolerance to salinity was also evident in the study of Hand et al. [54], in which the interaction between genotype and salinity had no effect on leaf Mg concentration during the vegetative growth stage.

5. Conclusions

This research shows that different pepper landraces respond differently to saline stress. This study investigated the impact of moderate salinity on pepper plants and found that it improved the quality of the fruit attributes by increasing the levels of TSSC (°Brix) and TA. Jordanian traditional varieties generally exhibit greater resilience to saline environments due to the elevated K/Na ratio in their leaves and fruits. Among the tested pepper cultivars, the landraces 'JO 109', 'JO 204', and 'JO 207' demonstrate the highest tolerance to salinity. This is substantiated by sustained yield, preservation of quality characteristics, and stable concentrations of most macronutrients, particularly K and Na, in the plant tissues under mild salinity stress conditions. The resilience of these cultivars is attributed to the fact that their fruit Na concentration remains unaffected under salt stress, ensuring that productivity remains intact. Consequently, these genotypes could potentially serve as potential sustainable rootstocks for pepper or in breeding programs for cultivation in areas affected by salinity stress. Leveraging the distinctive characteristics of these varieties has the potential to enhance pepper cultivation in challenging salinity conditions and foster the development of more resistant crop varieties.

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