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Research Article
(Araştırma Makalesi)

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Evaluation of salinity tolerance in tomato using morphological and nutritional traits*

Morfolojik ve besinsel özellikleri kullanarak domateste tuz toleransının değerlendirilmesi

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ABSTRACT

Objective: Research into different levels of salt tolerance in tomato varieties is important for agricultural production. In this study, the salt tolerance of cultivated, wild, and their hybrid tomato genotypes was investigated under hydroponic conditions.

Material and Methods: The plant material included two commercial cultivars, ten wild species (*Solanum pimpinellifolium* and *S. habrochaites*) and their hybrids. The plants were grown for 30 days under control (1.0 dS m^{-1}) and saline (10.0 dS m^{-1}) conditions. Principal component and correlation analyses were applied to determine their salt tolerance.

Results: Salt stress affected the fresh and dry weights of shoots and roots, especially in cultivars. Under salt stress conditions, genotype SP-4 had the tallest plants and the best chlorophyll index. The highest root volume was observed in SC2121xSP-2 hybrids. Instead of leaf K/Na ratio, genotype SP-1 had the highest value (0.57), while the lowest values were found in cultivars. Under salt stress, the highest leaf Ca content was found in genotype SH-4 (2.17%) and the lowest in genotype H2274 (0.70%). In terms of root Ca content, genotype SH-2 had the highest value under salt stress (1.79%). In stressed plants, Na levels were higher in cultivated plants and lower in wild and hybrid combinations. In contrast, Ca and K levels were higher in wild lines and hybrid combinations and lower in cultivated plants.

ÖZ

Amaç: Yabani ve kültür domates türlerinin tuzluluk toleransı farklılıkları, tarımsal üretim açısından önemli bir araştırma konusudur. Araştırmada, kültür, yabani ve bunların melezleri olan domates genotiplerinin tuza karşı toleransı hidroponik ortamda incelenmiştir.

Materyal ve Metot: Bitki materyali, iki ticari domates çeşidi, on yabani domates türü (*Solanum pimpinellifolium* ve *S. habrochaites*) ve bunların melezlerini içermektedir. Bitkiler kontrol (1.0 dS m^{-1}) ve tuzlu (10.0 dS m^{-1}) koşullarda 30 gün yetiştirilmiştir. Çalışma materyallerinin tuza tolerans seviyelerini belirlemek üzere, temel bileşen ve korelasyon analizleri uygulanmıştır.

Araştırma Bulguları: Tuz stresi, özellikle kültür çeşitlerinde sürgün ve köklerin taze ve kuru ağırlıklarını etkilemiştir. Tuz stresi koşullarında, genotip SP-4 en uzun bitkilere ve en iyi klorofil indeksine sahiptir. En yüksek kök hacmi ise SC2121xSP-2 melezlerinde gözlemlenmiştir. Yapraktaki K/Na oranı açısından, genotip SP-1 en yüksek değere (0.57) sahipken, en düşük değerlerse kültür çeşitlerinde tespit edilmiştir. Tuz stresi altında en yüksek yaprak Ca içeriği genotip SH-4'te (2.17%) ve en düşük genotip H2274'te (0.70%) bulunmuştur. Kök Ca içeriği açısından, genotip SH-2 tuz stresi altında en yüksek değere sahipti (%1.79). Stres altındaki bitkilerde, Na seviyeleri kültür bitkilerinde daha yüksek, yabani ve melez kombinasyonlarda ise daha düşük bulunmuştur. Buna karşılık, Ca ve K seviyeleri yabani hatlarda ve melez kombinasyonlarda daha yüksek, kültür bitkilerinde ise daha düşük bulunmuştur.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.), which belongs to the Solanaceae family, is a vegetable widely cultivated in arid and semi-arid regions in the world. Its production in controlled environments is also increasing steadily. In 2021, tomatoes were one of our leading agricultural products, with an impressive production of approximately 182 million tons from an area of around 5 million hectares (FAO, 2021). Beyond its economic significance, the tomato is highly nutritious. The cultivation of tomatoes has expanded into semi-arid and arid regions, where soil salinity poses a persistent and significant challenge (Raza et al., 2018). Tomatoes exhibit a wide genetic diversity, displaying various levels of tolerance to salt stress (Nveawiah-Yoho et al., 2013).

Salinity is an important environmental stress factor that adversely affects plant growth and development. Important agricultural crops such as tomato (*Solanum lycopersicum*) suffer yield losses when grown in saline soil conditions, and this situation threatens food security. In this context, the investigation of salinity tolerance mechanisms in wild tomato species is crucial for both agricultural applications and genetic improvement studies (Razali et al., 2018; Bonarota et al., 2021).

Wild tomato varieties generally have a higher salinity tolerance than cultivated varieties. This is related to the genetic diversity and adaptability of wild species. For example, wild species such as *Solanum pimpinellifolium* carry genes that are more resistant to salt stress, and their conservation could be used as a resource to improve the salinity tolerance of cultivars (Zaki & Yokoi, 2016; Razali et al., 2018). Salinity tolerance in wild species is often associated with physiological processes such as osmoregulation, ion balance, and antioxidant defense mechanisms (Palaniyandi et al., 2014; Alharby, 2021).

Cultivated tomato varieties have often been selected for higher yield and fruit quality, but important traits such as salinity tolerance have been overlooked. The process of domestication has resulted in genetic changes that reduce salinity tolerance (Wang et al., 2020). For example, variations in Na+/K+ transporters have been cited as a major cause of loss of salinity tolerance (Wang et al., 2020; Horváth, 2023). Therefore, gene transfer from wild species is recommended to improve the salinity tolerance of cultivars (Rao et al., 2012; Zaki & Yokoi, 2016).

In addition, another important issue is that it is essential to grow healthy seedlings and plants to obtain healthy, high quality and productive products in crop production (Khah, 2005; Yarşi & Sarı, 2006). With strong and dense root structures, plants should be able to extract more water and nutrients from the soil and transfer them to the leaves. This can only be achieved by using plants with strong roots or seedlings grafted on strong rootstocks (Ulaş et al., 2019; Aydın & Başak, 2023; Aydın, 2024a, b). In this context, it is very important to compare wild species, cultivated tomato varieties and their hybrids with each other to determine their potential as rootstocks. Finally, studies on the salinity tolerance of wild tomato lines provide important information on how these species can be used in agricultural applications. The identification of salt-tolerant genotypes enables the development of new salt-tolerant tomato cultivars by crossing these genotypes with cultivars (Zaki & Yokoi, 2016; Bonarota et al., 2021). Such studies play a critical role in the development of breeding programs to improve agricultural productivity and quality and ensure food safety, especially in identifying specific physiological traits and understanding these processes that confer salinity tolerance.

Genetic evaluation of salinity tolerance in wild tomato species is important to understand the mechanisms of salinity tolerance in these species. Multivariate analysis is recognized as a reliable method to evaluate salinity tolerance (Rehman et al., 2019; Alam et al., 2021). Such analyses reveal how different genotypes are grouped with respect to salinity tolerance and which traits contribute to this tolerance. For example, some genotypes exhibit morphological traits such as increased root and shoot length in response to salt stress (Rao et al., 2012; Ulaş et al., 2020; Alam et al., 2021; Başak et al., 2025). Furthermore, many researchers working with diverse vegetable species have proposed the utilization of

multivariate analyses (e.g. Principal Component Analysis) as a valid tool for germplasm collection and characterization (Aydın & Başak, 2023; Aydın & Yetişir, 2023; Şavkan & Türkmen, 2023; Pınar et al., 2024; Aydın, 2025; Şavkan et al., 2025a, b; Aydın et al., 2026).

In conclusion, differences in salinity tolerance between wild tomato lines and cultivars are an important area of research for agricultural production. The genetic diversity and adaptive capacity of wild species can be considered as a resource to confer tolerance to salinity stress. Understanding the mechanisms of salinity tolerance has great potential for both genetic improvement and agricultural applications. In this context, research on salinity tolerance of wild tomato species will provide an important basis for future agricultural applications.

MATERIALS and METHOD

Plant material

The study was conducted in 2021 at the fully automated R&D greenhouse of Kırşehir Ahi Evran University. The study plant material consists of types two open pollinated commercial tomato cultivars (SC2121, H2274), five *S. pimpinellifolium* lines, five *S. habrochaites* wild tomato lines and six hybrid combinations (Table 1).

Table 1. *Genotypes used in the study and species names*
Çizelge 1. Çalışmada kullanılan genotipler ve tür isimleri

Genotype Code	Type name and hybrid combination
SP-1	*S. pimpinellifolium (LA0373)*
SP-2	*S. pimpinellifolium (LA0417)*
SP-3	*S. pimpinellifolium (LA1269)*
SP-4	*S. pimpinellifolium (LA2914)*
SP-5	*S. pimpinellifolium (LA1279)*
SH-1	*S. habrochaites (LA1764)*
SH-2	*S. habrochaites (LA2114)*
SH-3	*S. habrochaites (LA1378)*
SH-4	*S. habrochaites (LA2163)*
SH-5	*S. habrochaites (LA2650)*
H2274	*S. lycopersicum (open pollinated commercial cultivar)*
SC2121	*S. lycopersicum (open pollinated commercial cultivar)*
H2274 x SH-1	*S. lycopersicum x S. habrochaites (h)*
SH-1 x H2274	*S. habrochaites x S. lycopersicum (cross-breed)*
SP-2 x SC2121	*S. pimpinellifolium x S. lycopersicum (cross-breed)*
SP-2 x H2274	*S. pimpinellifolium x S. lycopersicum (cross-breed)*
SC2121 x SP-2	*S. lycopersicum x S. Pimpinellifolium (cross-breed)*

Growth conditions and salt stress applications

For seedling production, tomato seeds were sown in a peat and perlite mixture (2:1, v/v) with an electrical conductivity (EC) of 0.36 dS m^{-1} and a pH of 6.0-6.5. The seedlings were grown until they developed 2-3 true leaves. The seedlings were transplanted 35 days after sowing.

Salt stress studies were conducted under hydroponic conditions. The composition of the hydroponic culture solution was prepared to contain 1500 µM Ca (N03)2, 750 µM K2SO4, 650 µM MgSO4, 500 µM KH2PO4, 10 µM H3BO3, 0.5 µM MnSO4, 0.5 µM ZnSO4, 0.4 µM CuSO4, 0.4 µM MoNa2O4 and 80 µM Fe EDDHA (EC 1.00 dS m-1). Distilled water was used for the preparation of the solution. The solution density was kept 10% lower than the above level, and the solution density reached the desired density on the 6th day.

Salt application was initiated 2 days after planting, and the salinity level was increased by 2 dS m^{-1} at two-day intervals, reaching the final concentration of 10 dS m^{-1} on the 6th day. Salt application was

done by adding NaCl to the nutrient solution. In addition to the salt stress treatments, the same genotypes were grown under control conditions (1.00 dS m^{-1}) and the salt injury rate was determined in % compared to the control conditions. The water culture medium was replaced every seven days from the beginning of the salt stress treatment. Six plants of each genotype were used for hydroponic culture.

Morphological measurements

When eighteen genotypes were evaluated for growth characteristics, plant height was determined in cm, root diameter (cm^2), length (m) and volume (cm^3) were determined using WinRhizoRegular LA2400, Regent Instruments root imaging program. Fresh weights of shoot (leaf + stem) and root of the seedlings were determined at the end of the experiment by separating the plants into organs (leaf, stem and root) and first determining the fresh weight (g) on a precision balance (Shimadzu/AY220), and then dry weights (g) were determined by drying these plant organs in an oven at 65°C for 48 hours. Chlorophyll index (SPAD) measurements were performed with SPAD-502 (Minolta Corporation, Ltd., Osaka, Japan) on fully developed leaves in the middle of the stress period and one day before the end of the experiment.

Plant nutrient analyses

The total elements Ca, K, B, Na, Mg, P, Mn, S, Cu, Fe, and Zn were determined by ICP-OES in dry-burned plant samples as reported by Kacar & İnal (2008).

Statistical analysis

The data obtained in the study were analyzed by one-way ANOVA (analysis of variance) and Duncan's multiple comparison test ($p<0.05$) using the JMP-18 statistical computer package program to test the differences between the mean values of the plants between the control and salt-treated groups. The change between the control and salt treatments was calculated and interpreted as a percentage [(salt control)/ (control)*100]. The JMP-18 statistical program was used for principal component analysis (PCA) and correlation analysis.

RESULTS AND DISCUSSION

Morphological analysis

The results of the analysis of variance (ANOVA) indicated that genotype, salt stress, and the genotype × salt stress interaction had highly significant effects ($p<0.001$) on shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight. Fresh and dry shoot weights of salt-stressed plants were examined, and it was found that there was a statistically significant decrease in weight values compared to control plants. The mean dry and fresh weights of the vegetative parts were parallel to each other. When the fresh shoot weights of the control group were examined, genotype SC2121xSP-2 had the highest value with 318.15 g, while genotypes SH-4 and SH-5 had the lowest values with 44.75 g and 44.25 g, respectively. Under saline conditions, the highest fresh shoot weight was measured in genotypes SC2121xSP-2 (109.76 g) and SP-4 (108.69 g). When plant shoot dry weight was analyzed in the control group, genotype SC2121xSP-2 had the highest value with 32.53 g, while genotype SH-5 had the lowest value with 4.32 g. Under saline conditions, genotype SP-4 had the highest shoot dry weight with 15.37 g, while the lowest shoot dry weight was 2.25 g in genotype SH-5 (Table 2). Under control conditions, the highest fresh root weight was measured in genotype SC2121xSP-2 (29.70 g), followed by genotypes SP-4 (25.68 g) and SP-2xSC2121 (24.69 g) (Table 3). The fresh root weight of plants decreased with salt application. The lowest fresh root weight was measured in genotypes SH-2 (1.77 g), SH-5 (2.49 g) and H2274 (2.59 g) under saline conditions. The highest fresh root weight under saline conditions was measured in genotype SP-4 (21.16 g) as in control conditions. The dry weight of plants was generally parallel to the fresh root weight. Genotype SP-4 (2.99 g) had the highest dry root weight under saline conditions (Table 2). In our study, salt stress significantly affected the fresh and dry weights of shoot and

roots of plants, and it was found that the dry weights of plants exposed to salt stress decreased as well as the fresh weights of shoots and roots. However, the rate of decrease in root fresh and dry weights was lower than that of shoot fresh and dry weights. While shoot fresh weights decreased by 63.15%, root fresh weights decreased by 49.72%, shoot dry weights decreased by 55.83% and root dry weights decreased by 40.11%. Supporting our findings, Kuşvuran (2011) reported that plant dry weights decreased in 31 melon genotypes under salt stress and genotypes were negatively affected by salt stress at different rates. Similarly, it has been reported in pepper (Chartzoulakis & Klapaki, 2000) and tomato (Debouba et al., 2006) that plant fresh and dry weights decreased with increasing salt concentrations. Furthermore, in agreement with the previous studies, shoot development was more negatively affected by salt stress than the root of the plant. The genotypes showed different responses. The most affected plants were the cultivars (H2274 and SC2121).

Table 2. *Morphological parameters of tomato genotypes grown under control (1.00 dS m^{-1}) and salt stress (10.00 dS m^{-1}) conditions*
Çizelge 2. Kontrol (1,00 dS m^{-1}) ve tuz stresi (10,00 dS m^{-1}) koşullarında yetiştirilen domates genotiplerinin morfolojik parametreleri

Genotype	Stem Fresh Weight (gr)		Stem Dry Weight (gr)		Root Fresh Weight (gr)		Root Dry Weight (gr)	
	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress
SP-1	155.05fg	54.57e	21.20ef	7.60eg	16.75ef	7.68de	2.36be	1.08d
SP-2	188.35ef	72.94cd	21.74df	6.35gi	15.56f	8.03d	1.83df	0.70fh
SP-3	242.86cd	102.68ab	24.52cf	11.67c	19.75ce	15.97b	2.01cf	1.82b
SP-4	251.30bc	108.69a	25.29be	15.37a	25.68b	21.16a	2.60bd	2.99a
SP-5	130.97gh	93.16b	22.13df	12.42b	19.34ce	13.12c	3.39a	1.76bc
SH-1	111.66g	39.00f	12.13h	5.03ij	3.84i	2.58h	0.41g	0.36ij
SH-2	93.07h	34.16fg	10.44hi	5.98hi	4.32i	1.77h	0.49g	0.31ij
SH-3	206.20de	65.57d	20.79f	10.41cd	20.93c	6.27eg	2.12cf	1.02de
SH-4	44.75i	23.04g	7.01ij	3.82j	2.86i	2.64h	0.44g	0.44hj
SH-5	44.25i	23.67g	4.32j	2.25k	4.04i	2.49h	0.40g	0.23j
H2274	107.75h	33.31fg	10.25hi	7.16fh	8.47h	2.59h	0.81g	0.55hi
SC2121	133.91gh	40.65f	24.64cf	8.27ef	12.35g	4.89g	2.27cf	1.01df
H2274XSH-1	187.69ef	33.83fg	17.02g	3.54j	16.57ef	3.00h	1.58f	0.31ij
SH-1XH2274	276.40bc	64.85de	25.83bd	8.71ef	20.63cd	5.90fg	1.97cf	0.79eg
SP-3XSC2121	289.96ab	80.67c	27.68bc	12.65b	24.69b	12.14c	2.36be	1.92b
SP-3XH2274	236.71de	71.93cd	22.55df	7.72eg	17.56df	6.76df	1.67ef	0.73fh
SC2121XSP-2	318.15a	109.76a	32.53a	12.75b	29.70a	13.12c	3.09ab	1.53c
SC2121XSH-1	264.37bc	75.87cd	28.95ab	9.00de	24.54b	8.32d	2.74ac	0.99df
Mean.	182.41	62.69	19.95	8.37	15.98	7.69	1.81	1.03
Std Dev	83.97	28.98	7.99	3.63	8.31	5.45	0.95	0.73
Std Er. Mean	19.79	6.83	189	0.85	1.96	1.28	0.22	0.17
CV	46.03	48.27	40.11	6.57	52.02	4.98	52.38	0.67
Genotype	0.000		0.000		0.000		0.000	
Salt Stress	0.000		0.000		0.000		0.000	
Genotype*SaltStress	0.000		0.000		0.000		0.000	

Means that do not share a letter are significantly different.

The results of the analysis of variance (ANOVA) indicated that genotype, salt stress, and the genotype × salt stress interaction had highly significant effects (p<0.001) on root length, root volume, root diameter, plant length, and chlorophyll index. The root length of candidate tomato genotypes for rootstock significantly decreased due to salt treatment. Under control conditions, the genotypes with the highest root lengths were SP-3 (234.35 m), SP-4 (222.08 m), and SP-2xSC2121 (223.22 m), while SH-4 had the shortest root length at 37.84 m (see Table 3). In saline conditions, SP-4 recorded the highest root length at 124.81 m, whereas the variety H2274 had the shortest at 12.25 m. Regarding root volume, the

genotypes SC2121xSP-2 (26.28 cm³) and SC2121xSP-2 (25.74 cm³) exhibited the highest root volumes under control conditions, while SH-4 had the lowest at 3.61 cm³. In salt-stressed plants, the highest root volume was observed in the SC2121xSP-2 hybrid (13.10 cm³), and the lowest was found in the SH-3 genotype (1.64 cm³). The application of salt caused an increase in root diameter for some genotypes (SP-1, SP-5, SH-2, SH-3, SH-4, SH-5, H2274XSH-1, and SH-1XH2274), while it decreased for others. The largest root diameter was measured in the hybrid SH-1xH2274 at 0.52 cm² under saline conditions (Table 3).

Table 3. *Morphological parameters of tomato genotypes grown under control (1.00 dS m^{-1}) and salt stress (10.00 dS m^{-1}) conditions*
Çizelge 3. Kontrol (1,00 dS m^{-1}) ve tuz stresi (10,00 dS m^{-1}) koşullarında yetiştirilen domates genotiplerinin morfolojik parametreleri

Genotype	Root length (m)		Root volume (cm³)		Root diameter (cm²)		Plant length (cm)		Chlorophyll index (SPAD)	
	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress
SP-1	168.22e	58.16de	12.51e	8.29cd	0.31i	0.43e	97.75a	61.75b	50.83bd	42.23de
SP-2	190.35ce	58.44de	20.04bc	5.65f	0.37d	0.36g	98.00a	48.50cd	49.78ce	42.38de
SP-3	234.35a	103.93b	22.09b	7.24de	0.35g	0.30m	92.00ab	48.00ce	49.25de	41.55de
SP-4	222.08ab	124.81a	18.93c	8.62c	0.34h	0.30n	83.33bc	72.75a	52.00bc	42.65ce
SP-5	164.38e	97.56b	11.30e	7.01de	0.30i	0.31l	77.00ef	45.25df	49.83ce	46.95ac
SH-1	42.17g	17.17g	6.02gh	2.31gi	0.43a	0.42f	82.75bd	47.75ce	47.8de	46.95ac
SH-2	41.96g	14.03g	4.00h	1.99hi	0.35f	0.43eg	66.50gh	42.25ef	47.35e	43.33ce
SH-3	198.91bd	20.30g	12.19e	1.64i	0.29j	0.33j	83.75cd	62.00b	41.80f	36.50f
SH-4	37.84g	15.57g	3.61h	2.20gi	0.37d	0.43ef	47.00i	34.00gh	40.78f	34.80f
SH-5	42.35g	16.31g	4.12h	2.77gi	0.36e	0.47c	33.25j	24.00i	48.28de	49.70ab
H2274	56.74g	12.25g	5.47h	2.57gi	0.36e	0.32k	39.00j	28.75hi	47.83de	43.68ce
SC2121	94.28f	21.38g	8.54fg	3.52g	0.43a	0.34i	62.25h	31.00gh	48.58de	40.75e
H2274XSH-1	117.37f	16.40g	10.25ef	3.28gh	0.34h	0.51b	68.00fg	34.75g	51.20bd	49.30ab
SH-1XH2274	179.44de	35.00f	15.59d	7.22de	0.34h	0.52a	75.50ef	35.75g	51.13bd	49.33ab
SP-2XSC2121	223.22ab	81.62c	25.74a	7.67ce	0.39c	0.35h	80.00ce	48.50cd	53.20ab	43.00ce
SP-2XH2274	164.84e	50.05e	15.70d	6.40ef	0.35f	0.41f	79.75ce	45.25df	55.78a	45.43bd
SC2121XSP-2	218.93bc	101.90b	26.28a	13.10a	0.40b	0.41f	87.50bc	52.50c	53.46ab	49.93a
SC2121XSH-1	202.09bd	62.58d	18.41c	10.21b	0.35f	0.46d	80.75de	41.50f	53.38ab	45.98ad
Mean	144.42	50.41	13.38	5.65	0.36	0.39	74.12	44.68	49.57	44.14
Std. Dev.	72.99	37.52	7.40	3.29	0.038	0.071	18.59	12.53	3.80	4.30
Std Er. Mean	17.20	8.84	1.74	0.78	0.009	0.017	4.38	2.95	0.90	1.01
CV	50.54	74.41	55.33	58.24	10.73	17.91	25.08	28.04	7.67	9.73
Genotype	0.000		0.000		0.000		0.000		0.000	
Salt Stress	0.000		0.000		0.000		0.000		0.000	
Genotype*SaltStress	0.000		0.000		0.000		0.000		0.000	

Means that do not share a letter are significantly different.

The effect of salt stress on plant root length decreased with salt stress (mean decrease 65.94%) and this decrease was higher than the decrease in stem length and leaf weight loss. The highest plant root length was obtained in SP-4 (124.81 m) and the lowest root length was obtained in H2274 genotype (12.25 m). A root length of 35 m was measured in the SP-2x H2274 hybrid genotype. The hybrid combination crossed with the wild line had more root length than the standard varieties H2274 and SC2121. The hybrid combination SC2121xSP-2 had the highest root volume compared to the cultivars and wild lines. The inhibition rate of seedling root length (41.74%) was higher than the inhibition rate of stem length (47.95%), indicating that roots were more affected by salt stress (Aydın, 2025). In another study, NaCl application inhibited root and stem elongation in tomato plants (Sekmen et al., 2005). Our study suggests that one of the most important reasons for the decrease in plant biomass is the disruption of ion balance as a result of increased Na and Cl content, ion toxicity and physiological dryness caused by salt stress.

Plant height varied between 33.25 (SH-5) and 98.88 (SP-2) cm under control conditions and between 24.00 (SH-5) and 72.75 (SP-4) cm under saline conditions (Table 3). Regarding chlorophyll index, the highest Chlorophyll index was generally measured in hybrid genotypes under control conditions. Under control conditions, the highest Chlorophyll index was recorded in SP-2xH2274 (55.78), SC2121xSP-2 (53.46), SC2121xSH-1 (53.38), SP-2xSC2121 (53.20) genotypes. Under saline conditions, the highest Chlorophyll index was measured in genotype SC2121xSP-2 (49.93) and the lowest Chlorophyll index was measured in genotype SH-4 (34.80) (Table 3). Salinity is a factor that affects the entire metabolism of the plant, including morphology and anatomy, and it has been reported in previous studies that plant growth may stop completely if stress conditions persist (Ashraf & Wu, 1994). In salt stress studies, it was reported that plant height decreased in melon (Franco et al., 1993) and okra (Kuşvuran, 2011) under saline conditions. In our study, plant height decreased between 13% and 53% with salt stress and the highest plant height was measured in SP-4 genotype under salt stress conditions. In order to protect the limited water taken up by the plant under stress conditions, some mechanisms are activated to, firstly stomata are closed and as a result a decrease in the amount of photosynthesis is observed (Süyüm, 2011). In terms of plant Chlorophyll index, the best result was generally obtained in cultivars crossed with wild lines. In another study conducted by Han-Zhiping et al. (2008) on watermelon (cv. Zaochun-hongyu), it was reported that there was a significant decrease in the amount of net photosynthesis with increasing NaCl concentration.

Principal Component Analysis (PCA) is used to identify variability within data, helping to distinguish between different groups. In our analysis of the morphological characteristics of tomato genotypes tested under salt conditions, we found that the first principal component (PC-1) accounted for 18.8% of the total variation, while the second principal component (PC-2) explained 67.2% of the variation. Together, these two independent principal component axes represented a cumulative variation of 86.0%. Specifically, the following traits were positively significant on the PC-1: root length (0.389), plant fresh weight (0.388), plant dry weight (0.384), root fresh weight (0.398), and root dry weight (0.365). On the PC-2, the significant traits included root volume (0.422), root diameter (0.509), and chlorophyll index (0.700). The two-dimensional bi-plot generated from this analysis illustrates the distribution of the lines along the PC-1 and PC-2 axes (Figure 1). Under salt stress conditions, the highest biomass parameters were obtained from SP-4, SP3 and SP-5 wild tomato lines, followed by hybrid combinations created using these wild lines. The lowest biomass parameters were obtained from open pollinated varieties and wild lines belonging to the species *S. habrochaites*.

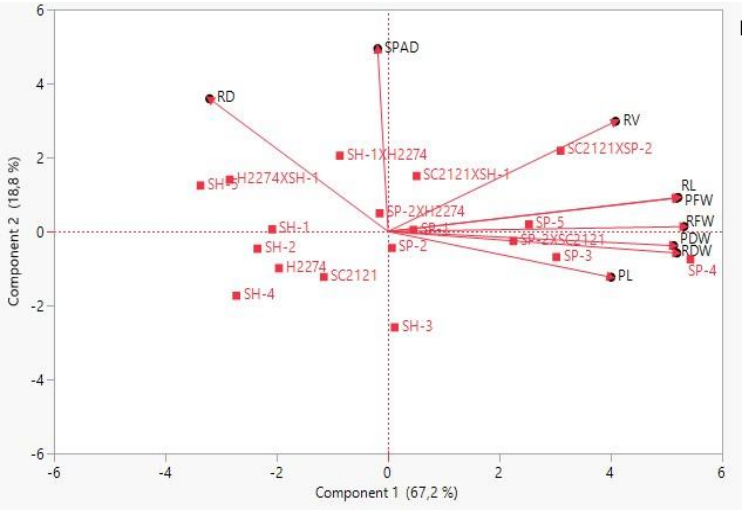


Figure 1. *Bi-plot analysis of morphological characteristics of salt stressed plants.*

Şekil 1. Tuz stresi altındaki bitkilerin morfolojik özelliklerinin bi-plot analizi.

Plant nutrient analysis

The results of the analysis of variance indicated that genotype, salt stress, and the genotype × salt stress interaction had highly significant effects (p<0.001) on all the examined traits (Table 4). With salt application, there was a notable decrease in leaf potassium (K) content and a significant increase in Na content in the plants. The genotype with the highest K content was SP-4, measuring 2.29%, while the lowest was found in genotype H2274, at 1.37%. Among the different genotypes, the most substantial decrease in K content was observed in genotype H2274 at 53%, whereas the lowest decline occurred in genotype SC2121xSP-2, at 20% under saline conditions. In terms of leaf Na content, salt application resulted in an increase ranging from 1193% to 4371%. The highest Na content was measured in genotype SH-1 at 5.03%, while the lowest was in genotype SP-2 at 3.63%.

Table 4. *Leaf and root K (%), Na (%), K/Na (ratio) contents of tomato genotypes grown under control (1.00 dS m^{-1}) and salt stress (10.00 dS m^{-1}) conditions*

Çizelge 4. Kontrol (1,00 dS m^{-1}) ve tuz stresi (10,00 dS m^{-1}) koşullarında yetiştirilen domates genotiplerinin yaprak ve kök K (%), Na (%), K/Na (oran) içerikleri

Genotype	Leaf						Root					
	K (%)		Na (%)		K/Na		K (%)		Na (%)		K/Na	
	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress
SP-1	3.39a	2.31a	0.16i	4.06i	21.29b	0.57a	2.06m	1.45m	0.14c	2.60g	14.77k	0.56l
SP-2	2.43p	1.69ef	0.28a	3.63k	8.64m	0.47b	2.10j	1.83c	0.13d	2.46h	15.90hi	0.74f
SP-3	3.10c	2.09b	0.15j	4.40f	20.15c	0.47b	1.43s	1.17r	0.09h	1.72p	15.32j	0.68i
SP-4	2.95d	2.29a	0.20e	4.85cd	15.01i	0.47b	1.72p	1.46ı	0.11g	1.86o	15.55hj	0.78d
SP-5	3.25b	1.94d	0.27b	4.43f	11.89l	0.44c	1.59r	1.43n	0.12f	3.32c	12.94m	0.43s
SH-1	2.60k	1.68ef	0.11l	5.03a	23.15a	0.33g	2.81b	1.71e	0.13e	3.59a	22.44e	0.48p
SH-2	2.33r	1.75e	0.28a	4.89bc	8.31n	0.36ef	2.52c	2.26a	0.07j	1.28s	36.60b	1.77a
SH-3	2.73g	2.09b	0.16h	4.91b	16.56f	0.42cd	2.26g	1.65h	0.09h	2.17l	25.40d	0.76e
SH-4	2.04s	1.48h	0.15j	4.31g	13.83j	0.34fg	2.20h	1.97b	0.06k	1.39r	39.44a	1.42b
SH-5	2.53m	1.60fg	0.14k	4.30g	18.15e	0.37e	2.97a	1.46ı	0.18a	2.80e	16.20h	0.52m
H2274	2.88e	1.37i	0.18f	4.79e	16.37g	0.28i	2.41f	1.39p	0.13d	2.72f	18.74f	0.51n
SC2121	2.74f	1.76e	0.14k	4.85cd	19.88d	0.36ef	1.83o	1.68f	0.11g	2.29k	16.03hi	0.74h
H2274XSH-1	2.51n	1.51gh	0.20e	4.80de	12.38l	0.31h	2.08k	1.73d	0.12f	2.33j	17.61g	0.74g
SH-1XH2274	2.69i	1.57gh	0.20d	4.28gh	13.16k	0.37e	2.44e	1.66g	0.09i	1.88n	28.68c	0.88c
SP-2XSC2121	2.72h	2.04bc	0.17g	4.75e	16.23g	0.43cd	1.88n	1.51k	0.13d	3.33b	14.06l	0.45r
SP-2XH2274	2.67j	1.87d	0.17g	3.85j	15.37h	0.49b	2.07ı	1.41o	0.18a	2.13m	11.51n	0.66j
SC2121XSP-2	2.49o	1.99bc	0.21c	4.23h	12.02l	0.47b	2.16i	1.53j	0.12f	3.13d	18.50f	0.49o
SC2121XSH-1	2.54l	1.76e	0.16hi	4.29g	15.45h	0.41d	2.50d	1.55i	0.14b	2.36i	17.31g	0.66k
Mean	2.70	0.41	0.19	4.48	15.44	1.82	2.17	1.60	0.12	2.41	19.83	0.74
Std. Dev.	0.33	0.074	0.049	0.39	4.09	0.27	0.40	0.25	0.03	0.66	7.87	0.34
Std Er. Mean	0.077	0.018	0.012	0.094	0.96	0.065	0.09	0.06	0.001	0.15	1.86	0.081
CV	12.15	18.20	26.56	8.90	26.50	15.03	18.52	15.42	26.89	27.40	39.69	46.58
Genotype	0.000		0.000		0.000		0.000		0.000		0.000	
Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	
Genotype*Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	

Means that do not share a letter are significantly different.

Regarding the leaf K/Na ratio under saline conditions, the highest ratio was found in genotype SP-1 at 0.57, and the lowest was in genotype H2274 at 0.28. Overall, salt application reduced the K/Na ratio of the plants by 95% to 98%. When root K and Na nutrient contents were analyzed, K and Na contents were significantly affected by salt application as in leaves. Root K content decreased with salt application. The greatest decrease in K content was observed in genotypes SH-5 (51%) and H2274 (42%). Under saline

conditions, the highest K content was measured in genotype SH-2 (2.26%) and the lowest K content was measured in genotype SP-3 (1.17%). Under saline conditions, the highest Na content was measured in genotype SH-1 (3.59%) and the lowest Na content was measured in genotype SP-3 (1.72%). Regarding root K/Na ratio, the highest K/Na ratio was obtained in genotype SH-2 (1.77) and the lowest in genotype H2274 (0.51) under saline conditions. In our study, root and leaf K content decreased, and Na content increased with salt stress. Regarding leaf K/Na ratio, the highest K/Na ratio was obtained in SP-1 genotype with 0.57, while this ratio was 0.28 in H2274 genotype and 0.36 in SC2121 genotype. The decrease in the K/Na ratio increases the degree to which the plant is affected by salt stress. In agreement with our results, previous studies reported that K content decreased and Na content increased in roots and shoots of plants exposed to salt stress (Akbarimoghaddam et al., 2011). Aboutalebi & Jahromi (2013) reported that potassium content in leaves decreased significantly when salt concentration increased from 80 mmol/L to 100 mmol/L in tomato cultivars. Afzall et al. (2014) in chilli under different salt stress conditions, reported that the increase in salinity caused a decrease in K concentration. Under salt stress conditions, sodium (Na) content tends to be high in cultivated plants and low in wild and hybrid varieties. In saline environments, plants absorb excessive amounts of Na, which inhibits the uptake of K and Ca. Elevated Na/Ca and Na/K ratios in saline soil can lead to the passive accumulation of Na in the roots and stems by disrupting the selectivity of root membranes. This high rate of Na accumulation in plant roots may occur due to regulatory mechanisms at specialized sites within the root. These mechanisms can prevent the transport of Na from the roots to the above-ground parts of the plant, resulting in Na buildup in the roots. The increased concentration of Na typically causes ion toxicity, disrupting osmotic regulation and nutrient balance (Köşkeroğlu, 2005).

When the effect of salt application on leaf B, Ca and Fe contents of plants was analyzed, it was observed that B and Ca contents of plants decreased with salt application (Table 5). The highest B content was measured in genotype SC2121xSH-1 (26.61 ppm) and the lowest B content was measured in genotype SH-1 (24.13 ppm) with salt application. The highest Ca content was measured in genotype SH-4 (2.17%) and the lowest Ca content was measured in genotype H2274 (0.70%) under saline conditions. The highest decrease in the effect of salt application on Ca content compared to control conditions was observed in genotype H2274 (45%). When Fe content was analyzed, the Fe content of all genotypes except SP-5, SH-3 and SH-5 genotypes decreased under saline conditions. Under saline conditions, the highest Fe content was observed in genotype SP-5 (1232.96 ppm), which showed an increase compared to the control group, while the lowest Fe content was measured in genotype H2274 (539.58 ppm). When root B element content was analyzed, there was a general decrease in B content with salt application. The highest P content was measured in genotypes SP-5 (44.51 ppm) and SH-3 (44.39 ppm) under saline conditions. Root Ca content was highest in genotypes SH-1 (1.79%) and SH-2 (1.70%) under saline conditions. The highest Fe content was measured in genotype SH-5 (75.71 ppm) and the lowest in genotype SC2121 (40.72 ppm) under saline conditions. The highest leaf Ca content under salt stress was measured in genotype SH-4 (2.17%) and the lowest in genotype H2274 (0.70%). With regard to root Ca content, the highest Ca content in salt stressed plants was measured in genotype SH-2 (1.79%). Increasing the Ca content in plant tissues increases the resistance of plants to salt stress. Ca and K contents were high in wild lines and hybrid combinations, but low in cultivars. These results help to explain why wild lines and hybrid combinations exhibit greater tolerance to salt stress compared with cultivated varieties. Wild genotypes generally possess more efficient ion-homeostasis mechanisms, allowing them to restrict excessive Na^+ and Cl^- uptake and to maintain a more balanced acquisition of essential nutrients under saline conditions (Aydın 2024a, b).

Table 5. *Plant leaf and root B (ppm), Ca (%), Fe (ppm) contents in tomato genotypes grown under control (1.00 dS m^{-1}) and salt stress (10.00 dS m^{-1}) conditions*

Çizelge 5. Kontrol (1,00 dS m^{-1}) ve tuz stresi (10,00 dS m^{-1}) koşullarında yetiştirilen domates genotiplerinde bitki yaprağı ve kök B (ppm), Ca (%), Fe (ppm) içerikleri

Genotype	Leaf						Root					
	B (ppm)		Ca (%)		Fe (ppm)		B (ppm)		Ca (%)		Fe (ppm)	
	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress
SP-1	31.85c	24.99fg	1.39j	0.79r	744.79n	571.15m	45.14f	41.58b	2.06j	1.24l	52.67m	55.43d
SP-2	33.21b	25.64d	1.76d	1.46c	1339.00b	984.71d	41.94g	34.17f	1.53r	1.16n	47.70n	41.29l
SP-3	29.87i	24.88g	1.23n	0.97m	789.86l	781.17h	45.00f	33.55f	2.08i	1.02p	57.02k	36.22m
SP-4	31.12e	24.89g	1.41i	0.89o	1117.96f	720.20j	47.49e	38.10c	2.03ı	1.09o	79.56b	57.29c
SP-5	30.10h	26.02bc	1.20o	1.41e	737.61n	1232.96a	58.37ab	44.51a	1.90m	1.32i	70.07de	43.40k
SH-1	27.70m	24.13i	1.49g	1.09l	695.48n	927.69f	45.26f	42.21b	1.69n	1.70a	58.59j	52.64f
SH-2	28.14l	25.21ef	1.74e	1.28g	1039.66h	771.26h	37.41i	35.14ef	2.35d	1.79a	69.62d	44.48k
SH-3	30.88f	25.76d	2.00b	1.71b	870.65j	963.31e	39.51h	44.39a	2.22f	1.54f	191.90a	58.18c
SH-4	31.59d	25.41e	3.31a	2.17a	639.05o	575.92m	54.41d	42.67ab	2.82a	1.63e	71.01d	57.35c
SH-5	29.23j	24.77g	1.84c	1.32f	479.27r	627.14l	48.49e	37.97c	2.18g	1.28k	59.16j	75.71a
H2274	30.53g	24.88g	1.28m	0.70s	579.84p	539.58n	55.82cd	42.01b	1.60p	1.20m	65.01h	61.45b
SC2121	29.75i	25.30e	1.18p	0.80p	923.36i	746.67i	58.64a	36.31ce	2.33e	1.31j	65.95g	40.72l
H2274XSH-1	29.63i	24.49h	1.51f	1.27h	1051.80g	782.76h	34.98j	35.39df	2.06j	1.74b	62.18i	49.78h
SH-1XH2274	28.82k	24.40h	1.43h	1.42d	818.99k	662.15k	38.00hi	31.58g	2.58b	1.73c	75.31c	53.70ef
SP-2XSC2121	30.90ef	26.21b	1.32l	1.18j	1138.21e	873.36g	58.93a	37.61c	2.41c	1.28k	78.57b	54.34de
SP-2XH2274	30.47g	23.99i	1.36k	0.95n	1225.24d	578.74m	56.56bc	35.29ef	2.12h	1.38h	78.95b	47.65i
SC2121XSP-2	34.02a	25.80cd	1.50g	1.16k	1545.54a	1014.68c	47.87e	36.63ce	1.65o	1.46g	55.77l	46.04j
SC2121XSH-1	31.48d	26.61a	1.74e	1.24i	1241.58c	1184.04b	59.58a	37.21cd	2.04k	1.32j	67.73f	51.10g
Mean	30.52	25.19	1.59	1.21	943.22	807.64	48.52	38.13	2.09	1.39	72.59	51.49
Std. Dev.	1.61	0.72	0.49	0.36	287.49	208.83	8.26	3.87	0.34	0.24	31.19	9.22
Std Er. Mean	0.38	0.17	0.12	0.085	67.76	49.22	1.95	0.91	0.080	0.056	7.35	2.17
CV	5.28	2.87	30.65	29.62	30.48	25.86	17.03	10.15	16.31	16.95	42.96	17.90
Genotype	0.000		0.000		0.000		0.000		0.000		0.000	
Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	
Genotype*Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	

Means that do not share a letter are significantly different.

Table 6 compares the P (%), S (%), and Zn (ppm) contents of leaf and root tissues in different tomato genotypes grown under control (1.0 dS m^{-1}) and salt stress (10.0 dS m^{-1}) conditions. Leaf P content generally showed a decreasing trend under salt stress. While leaf P values ranged from 1.02 to 1.50% under control conditions, they decreased to 0.65-1.23% under salt stress. The genotypes SH-1, SH-3, and SC2121 maintained relatively higher P contents in both leaves and roots, indicating a more tolerant nutritional profile under saline conditions. Root P content increased under salt stress in some genotypes (e.g., SH-1). Leaf S content exhibited either an increase or only minor changes under salt stress, depending on the genotype. On average, leaf S content increased from 0.67% to 0.71%, while root S content increased from 0.47% to 0.52%. Under control conditions, leaf Zn content varied between 11.79 and 39.64 ppm among genotypes, whereas under salt stress these values generally decreased to a range of 6.16-19.88 ppm. The mean leaf Zn content declined from 26.97 ppm under control conditions to 11.38 ppm under salt stress. Similarly, mean root Zn content decreased from 27.27 ppm under control conditions to 23.07 ppm under salt stress. However, the increase in root Zn content observed in some

genotypes under salt stress suggests that Zn was retained in the roots and its translocation to the shoots was restricted. Overall, salt stress suppressed Zn uptake by the plant, particularly its transport to the leaves, while the relative accumulation in roots was closely associated with genotypic differences. The reason for the decrease may be that the genotypes suffer from a deficiency of this element as a result of a partial decrease in Zn solubility under saline conditions (Pessarakli, 1999). Significant differences among genotypes were observed in P, S, and Zn contents in leaf tissues at the $p<0.001$ level, whereas differences in root tissues were significant at the $p<0.01$ level.

Table 6. *Plant leaf and root P (%), S (%), Zn (ppm) contents in tomato genotypes grown under control (1.00 dS m^{-1}) and salt stress (10.00 dS m^{-1}) conditions*

Çizelge 6. Kontrol (1,00 dS m^{-1}) ve tuz stresi (10,00 dS m^{-1}) koşullarında yetiştirilen domates genotiplerinde bitki yaprağı ve kök P (%), S (%), Zn (ppm) içerikleri

Genotype	Leaf						Root					
	P (%)		S (%)		Zn (ppm)		P (%)		S (%)		Zn (ppm)	
	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress
SP-1	1.06n	0.71r	0.71e	0.81c	1056.92h	851.93lm	1.06n	0.71r	0.71e	0.81c	1056.92h	851.93lm
SP-2	1.10k	0.98f	0.68f	0.66l	1351.97e	1016.51i	1.10k	0.98f	0.68f	0.66l	1351.97e	1016.51i
SP-3	1.06o	0.81n	0.70e	0.99a	1103.98g	1051.07h	1.06o	0.81n	0.70e	0.99a	1103.98g	1051.07h
SP-4	1.20f	0.89k	0.77a	0.80d	1342.34e	952.56j	1.20f	0.89k	0.77a	0.80d	1342.34e	952.56j
SP-5	1.25d	1.05c	0.72d	0.73g	899.95k	1471.86c	1.25d	1.05c	0.72d	0.73g	899.95k	1471.86c
SH-1	1.50a	1.23a	0.65i	0.82b	1619.07b	1988.25a	1.50a	1.23a	0.65i	0.82b	1619.07b	1988.25a
SH-2	1.17g	0.91i	0.61l	0.74f	1617.27b	1293.33f	1.17g	0.91i	0.61l	0.74f	1617.27b	1293.33f
SH-3	1.40c	1.22b	0.56m	0.61n	1605.15b	1935.34b	1.40c	1.22b	0.56m	0.61n	1605.15b	1935.34b
SH-4	1.44b	1.01e	0.64j	0.67k	1580.64c	836.6m	1.44b	1.01e	0.64j	0.67k	1580.64c	836.6m
SH-5	1.02p	0.90j	0.55n	0.65m	946.20j	1397.21e	1.02p	0.90j	0.55n	0.65m	946.2j	1397.21e
H2274	1.04o	0.78o	0.66h	0.76e	589.59l	636.23n	1.04o	0.78o	0.66h	0.76e	589.59l	636.23n
SC2121	1.08l	0.98g	0.67g	0.81c	993.41i	858.68l	1.08l	0.98g	0.67g	0.81c	993.41i	858.68l
H2274XSH-1	1.12i	0.77p	0.63k	0.68j	1602.97b	927.91k	1.12i	0.77p	0.63k	0.68j	1602.97b	927.91k
SH-1XH2274	1.10j	0.87m	0.56m	0.58o	1436.74d	1272.68g	1.10j	0.87m	0.56m	0.58o	1436.74d	1272.68g
SP-2XSC2121	1.14h	0.88l	0.73c	0.71h	1347.27e	933.83k	1.14h	0.88l	0.73c	0.71h	1347.27e	933.83k
SP-2XH2274	1.07m	0.65s	0.70e	0.53p	1235.29f	616.19o	1.07m	0.65s	0.70e	0.53p	1235.29f	616.19o
SC2121XSP-2	1.23e	0.94h	0.75b	0.69i	1982.01a	1012.79i	1.23e	0.94h	0.75b	0.69i	1982.01a	1012.79i
SC2121XSH-1	1.40c	1.03d	0.70e	0.58o	1966.67a	1438.53d	1.40c	1.03d	0.70e	0.58o	1966.67a	1438.53d
Mean	1.19	0.92	0.67	0.71	1348.75	1138.42	1.19	0.92	0.66	0.71	1348.75	1138.42
Std. Dev.	0.15	0.15	0.07	0.11	371.32	391.29	0.15	0.15	0.07	0.11	371.32	391.29
Std Er. Mean	0.035	0.036	0.015	0.026	87.52	92.23	0.035	0.036	0.015	0.026	87.52	92.23
CV	12.71	16.78	9.76	15.51	27.53	34.37	12.71	16.78	9.76	15.51	27.53	34.37
Genotype	0.000		0.000		0.000		0.006		0.009		0.007	
Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	
Genotype*Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	

Means that do not share a letter are significantly different.

Under saline conditions, the genotype SH-1 exhibited the highest leaf Cu content at 55.21 ppm, while the lowest leaf Cu content was found in the genotype H2274xSH-1 at 12.44 ppm. Leaf manganese (Mn) content showed marked genotypic variation under both control and salt stress conditions. Under control conditions, leaf Mn concentrations ranged from 20.89 to 86.08 ppm among genotypes, whereas under salt stress these values generally decreased to a range of 18.06-64.47 ppm. On average, leaf Mn content declined from 40.46 ppm under control conditions to 33.70 ppm under salt stress. Although salt stress suppressed Mn accumulation in the leaves of most genotypes, an increase in Mn content was observed in some genotypes, such as SH-1 and SH-5, suggesting the presence of genotype-specific mechanisms that maintain Mn uptake or translocation under saline conditions (Table 7).

Table 7. *Plant leaf and root Cu (ppm), Mn (ppm), Mg (%) contents in tomato genotypes grown under control (1.00 dS m^{-1}) and salt stress (10.00 dS m^{-1}) conditions*

Çizelge 7. Kontrol (1,00 dS m^{-1}) ve tuz stresi (10,00 dS m^{-1}) koşullarında yetiştirilen domates genotiplerinde bitki yaprağı ve kök Cu (ppm), Mn (ppm), Mg (%) içerikleri

Genotype	Leaf						Root					
	Cu (ppm)		Mn (ppm)		Mg (%)		Cu (ppm)		Mn (ppm)		Mg (%)	
	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress	Control	Salt Stress
SP-1	17.21m	13.79k	183.17i	131.77l	0.54m	0.47g	7.96gh	13.80b	21.19j	41.97e	0.21n	0.19k
SP-2	34.29i	17.11j	172.14j	168.56g	0.59k	0.40m	6.74i	9.66i	28.67gh	35.89f	0.24k	0.22h
SP-3	28.05k	24.21de	160.94l	128.80m	0.49o	0.47h	8.38fg	8.41j	25.07i	21.20i	0.25j	0.16l
SP-4	63.19b	17.76ij	188.70h	116.99o	0.52n	0.46i	9.59cd	11.25ef	35.71d	37.71f	0.28f	0.21i
SP-5	24.28l	27.17b	149.07m	182.50f	0.59k	0.49e	8.86ef	11.70d	30.89f	27.27h	0.21n	0.15m
SH-1	46.71f	55.21a	291.82c	322.36a	1.03a	0.56c	6.22i	9.92hi	23.30i	49.16c	0.19o	0.23g
SH-2	28.21k	24.92cd	430.41a	142.32j	0.97b	0.57b	12.42b	12.42c	28.44h	26.04h	0.23l	0.27c
SH-3	17.42m	20.00h	217.95d	240.55c	0.76f	0.58a	8.48eg	12.84c	23.77i	31.77g	0.22m	0.20j
SH-4	11.83n	11.92l	312.88b	216.70d	0.64j	0.39n	15.07a	10.89eg	30.46fg	30.89g	0.38b	0.34a
SH-5	10.94o	24.40d	168.56k	253.76b	0.87c	0.47h	9.18de	12.61c	20.10j	36.95f	0.32d	0.25d
H2274	31.47j	21.07g	104.46n	90.31r	0.76g	0.44j	12.62b	14.96a	32.97e	51.33b	0.43a	0.31b
SC2121	57.14c	26.52b	147.50m	119.11n	0.67h	0.53d	7.61h	11.46df	51.67a	40.39e	0.27gh	0.25d
H2274XSH-1	43.15g	12.44l	184.03i	200.08e	0.78e	0.58a	7.60h	12.75c	34.60de	36.79f	0.25j	0.31b
SH-1XH2274	36.24h	24.73cd	190.85g	144.49i	0.84d	0.48f	10.03c	12.52c	43.80b	49.70c	0.27h	0.27c
SP-2XSC2121	55.15d	22.79f	166.79k	134.99k	0.65i	0.43k	9.14ef	10.82eg	50.29a	41.76e	0.34c	0.24f
SP-2XH2274	52.30e	17.86i	162.54l	100.23p	0.64j	0.42l	9.37cd	10.39gh	38.82c	45.11d	0.32d	0.23g
SC2121XSP-2	68.51a	23.62e	214.13e	157.75h	0.57l	0.37o	6.75i	10.95eg	39.27c	54.42a	0.27g	0.25e
SC2121XSH-1	62.73b	25.19c	195.38f	182.17f	0.78e	0.40m	8.42eg	10.69fg	42.78b	44.68d	0.30e	0.24f
Mean	38.27	22.82	202.30	168.52	0.71	0.47	9.14	11.56	33.43	39.06	0.28	0.24
Std. Dev.	18.56	9.40	75.04	59.97	0.154	0.068	2.26	1.58	9.51	9.25	0.063	0.049
Std Er. Mean	4.38	2.22	17.69	14.13	0.036	0.016	0.532	0.372	2.24	2.18	0.015	0.012
CV	48.51	41.20	37.10	35.58	21.86	14.29	24.73	13.64	28.45	23.70	22.72	20.71
Genotype	0.000		0.008		0.000		0.000		0.000		0.000	
Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	
Genotype*Salt Stress	0.000		0.000		0.000		0.000		0.000		0.000	

Means that do not share a letter are significantly different.

Overall, these results indicate that salt stress adversely affected leaf Mn content, with the magnitude of the response being strongly genotype dependent. Leaf Mg content decreased by 5% to 49% across all genotypes with the application of salt. The genotype SH-3 had the highest Mg content at 0.58%, whereas genotype SC2121xSP-2 had the lowest Mg content at 0.37%. In terms of root content under saline conditions, genotype H2274 showed the highest Cu content at 14.96 ppm, while genotype SP-3 had the lowest Cu content at 8.41 ppm. The highest root Mn content was found in genotype SC2121xSP-2 at 54.42 ppm, and the lowest was in genotype SP-3 at 21.20 ppm. Under control conditions, the genotype H2274 had the highest root Mg content at 0.43%, while under saline conditions, the highest Mg content was observed in genotype SH-4 at 0.34%. In the tomato plant grown in the study, leaf iron content under salt stress ranged from 539.58 to 1232.96 ppm and it was found that the plants were adequately supplied with iron (40-100 ppm Fe) (Hochmuth & Hanlon, 2004). In our study, leaf P content was found to be between 0.65-1.23%, Mg content between 0.37-0.58%, B content between 23.99-26.61 ppm, Cu 11.92-51.21 ppm, Mn 90.31-322.36 ppm and Zn 616.19-1988.25 ppm under saline conditions and these elemental levels in leaves were sufficient for many genotypes tested. Therefore, among the genotypes used in the experiment, there are promising genotypes in terms of tolerance to salt stress.

In the principal component analysis of the nutrient properties of salt-treated tomato genotypes in leaves, the analysis revealed that the first principal component (PC-1) explained 34.2% of the total variation, while the second principal component (PC-2) accounted for 21.1% of the variation. Together, four independent principal component axes represented 81.73% of the cumulative variation. The analysis indicated that P (0.442), Zn (0.445), Mn (0.410), and Cu (0.336) had positive significance on PC-1, while B (0.476), Fe (0.397), and K (0.356) were positively significant on PC-2. Conversely, Na (-0.343) and Mg (-0.341) showed negative significance. When examining the principal component axes related to root nutrient properties of salt-treated tomato genotypes, the first principal component explained 27.3% of the total variation, and the second principal component explained 21.6% of the variation. Again, four independent principal component axes accounted for a cumulative variation of 79.70%. On PC-1, the parameters showing positive significance included the K/Na ratio (0.493), K (0.488), Ca (0.416), and Mg (0.379), with Na (-0.356) having a negative significance. For PC-2, the positively significant nutrients were Fe (0.396), B (0.393), Na (0.351), Zn (0.350), and P (0.335). The two-dimensional bi-plot analysis shows the distribution of the lines in the direction of PC-1, PC-2 axes (Figure 2). While a negative correlation was detected between the K and Ca plant nutrients and the Na nutrient element in the leaf and root tissues of plants under salt stress, a generally positive correlation was detected between the P, Zn, Mn, B, Fe, Ca plant nutrients.

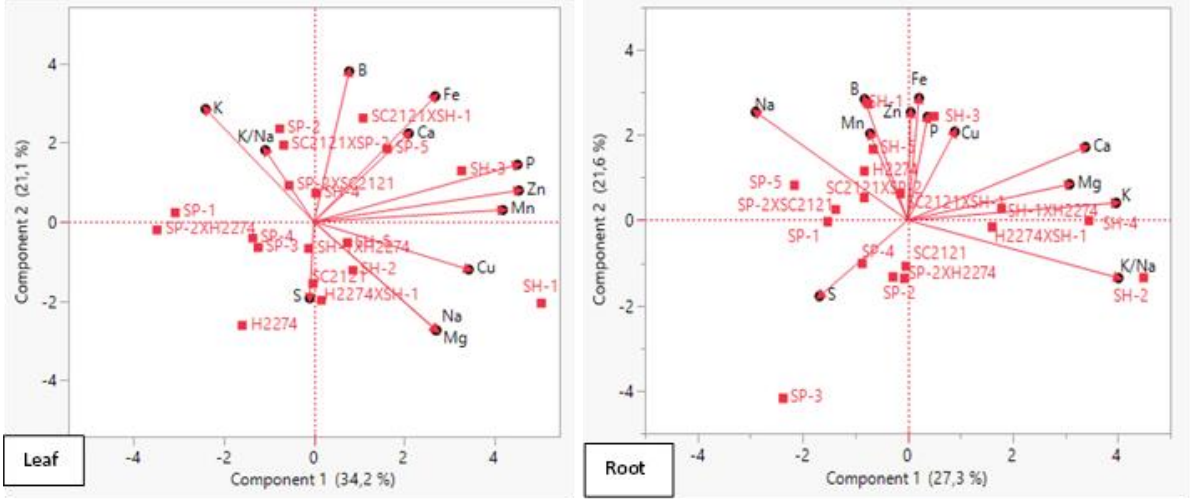


Figure 2. *Bi-plot analysis of nutrients in leaves and roots of salt stressed plants.*

Şekil 2. Tuz stresi altındaki bitkilerin yaprak ve köklerindeki besin maddelerinin bi-plot analizi.

Correlation analysis

Correlation analysis was employed to elucidate the relationships between plant nutrients (e.g. Fe, S, P and Na) and various morphological traits (e.g. plant dry weight, plant fresh weight, plant height, root diameter, root dry weight, root fresh weight, root length, root volume and chlorophyll index readings). The analysis revealed positive correlations between leaf K and plant fresh weight (0.674), plant dry weight (0.522), plant height (0.705), root fresh weight (0.641), root dry weight (0.550), root length (0.693) and root volume (0.656). Conversely, root K exhibited negative correlations with all parameters except root diameter (0.374). High negative correlations were observed between Na levels in the leaf and root volume (-0.432), while high positive correlations were observed between Na levels in the root and chlorophyll index (0.462). A robust positive correlation was identified between the levels of K/Na in leaves and various physiological characteristics of the plants, including plant height (0.863), plant dry weight (0.724), plant fresh weight (0.693), root dry weight (0.760), root fresh weight (0.747) and root length (0.713). A strong negative correlation was detected between leaf Mg and root volume (-0.608). Furthermore, a strong negative correlation was detected between root Mg and plant dry weight (-0.574),

plant fresh weight (-0.656), plant height (-0.595), root dry weight (-0.567), root fresh weight (-0.628) and root length (-0.63). However, no correlation was detected between root diameter (0.514) and the aforementioned variables. The presence of S has been observed in both leaves and roots.

A correlation analysis was conducted to ascertain the effects of salt stress on plant growth in both wild and cultivated tomatoes (Figure 3). This analysis revealed the critical role of certain nutrients in this process. In this context, while the accumulation of K in the leaves and the high K/Na ratio are important positive determinants of plant growth, excessive accumulation of certain nutrients (e.g. K, Mg, Fe, Ca) in the root can negatively affect growth.

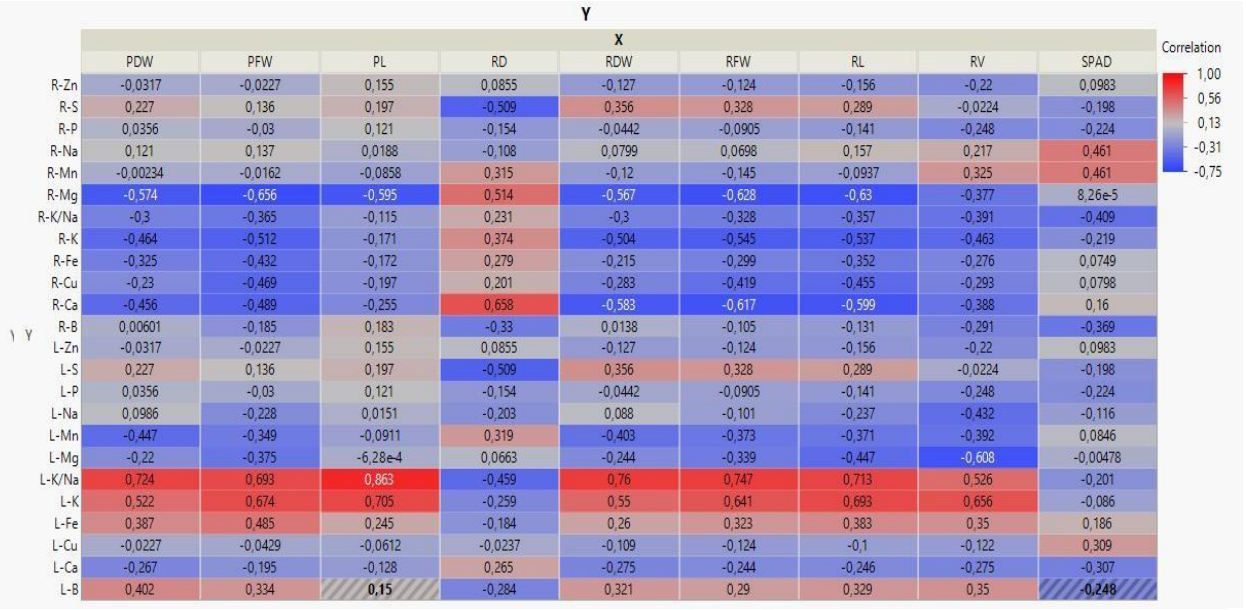


Figure 3. *Heat-map correlation analysis between plant nutrients and morphological parameters of salt stressed plants.*
Şekil 3. Bitki besin maddeleri ile tuz stresi altındaki bitkilerin morfolojik parametreleri arasındaki ısı haritası korelasyon analizi.

This finding underscores the pivotal role of ion balance in the root. K plays a vital role in plant life, functioning in the maintenance of water balance, the regulation of osmotic pressure, and the support of photosynthetic processes. Consequently, sufficient potassium levels are conducive to the optimization of plant biomass, height and root development. It has been demonstrated that potassium has the capacity to enhance plant stress tolerance and promote growth by reducing water loss, particularly in conditions of salt stress (Munns & Tester, 2008). Conversely, the Na content of leaves and roots has been found to be inversely associated with numerous morphological parameters. In particular, the negative correlation of leaf Na with root volume suggests that sodium may limit cell expansion by inducing osmotic stress, especially at high concentrations. Sodium has been demonstrated to be toxic to plants and to increase salt stress by inhibiting water uptake (Munns, 2002). This is a factor that poses a threat to the overall health and productivity of the plant. Once more, elevated magnesium levels in the root exhibited robust negative correlations with pivotal growth indicators, including plant fresh and dry weight, height, and root length. This finding suggests that excess Mg may suppress development through antagonistic relationships with some ions (especially Ca and K).

CONCLUSION

As a result, this study, under salt stress conditions; Na content was higher in cultivars and lower in wild and hybrid combinations. In contrast, Ca and K contents were significantly higher in wild lines and hybrid combinations, but lower in cultivars. In conclusion, correlation analysis provides important information that should be considered when developing plant nutrition strategies. It was concluded that the provision of appropriate levels of nutrients such as potassium is critical to optimize plant growth, while the avoidance of excessive levels of elements such as sodium and magnesium is also recommended. In the context of plant nutrition practices, the recommendation is to increase potassium and K/Na supplementation, whilst concurrently controlling sodium and magnesium levels, with a view to minimizing the effects of salt stress. The implementation of these strategies has been demonstrated to enhance the resilience of tomato plants to salt stress, thereby promoting enhanced overall productivity. Consequently, interspecific crosses can be regarded as a promising strategy for enhancing salt resistance in tomato. Furthermore, it is not solely the quantity of nutrients that is pertinent to development; the specific organ in which they are located and their ratio to other elements are also of consequence. These findings suggest that fertilization strategies should be optimized based not only on the amount of nutrients applied, but also on the form, location (leaf/root) and timing of application. Salt-sensitive plants absorb ions uncontrollably in saline environments. Since these plants lack the ability to store the high levels of salt they absorb, this causes damage to the plant. This damage is not osmotic stress but rather results from ion toxicity. Another type of salinity stress occurs in the root region. When salt-sensitive plants encounter high concentrations of salt, root development is inhibited and they are also affected by salt toxicity. The second type of salinity stress primarily occurs in the roots, but growth limitations and toxicity symptoms are more evident in the shoots. Thus, salinity stress manifests itself in plants as a result of the combined effects of internal and external factors.

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Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: AA, HY, HB; sample collection: AA, ANŞ, AB; analysis and interpretation of data: AA, AB, ANŞ; statistical analysis: AA, ANŞ; visualization: HB, HY; writing manuscript: AA, ANŞ, HB.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that an ethics committee is not required for this study.

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