



Identifying Salt-Tolerant Chickpea Genotypes During Early Growth Stage Through Multi-Statistical Approaches and Stress Indices Under Saline Conditions

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ABSTRACT

Salinity is an important environmental factor that jeopardizes productive agriculture in our world with the increasing human population, significantly limiting the production of food products and negatively affecting the growth and development of plants. In this study, eight chickpea (*Cicer arietinum* L.) genotypes from Türkiye were germinated under salt stress such as sodium chloride (NaCl) and sodium sulfate (Na₂SO₄) at electrical conductivity levels (4, 8, 12 and 16 dS m⁻¹) over a period of 10 days in order to evaluate seed germination, seedling morphological and mineral responses, and to determine tolerant genotypes. Salinity stress is considered as one of the major constraints in chickpea production, but our study revealed a remarkable diversity among

the tested genotypes. Germination rates decreased significantly with increasing salinity levels. While germination rates of different chickpea genotypes were above 85% under control conditions, these rates varied between 21% and 91% at the highest salt treatment of 16 dS m⁻¹ of both salts. Sodium, calcium and sulfur contents showed significant differences among the genotypes. As the salt concentrations increased, the Na/K ratio also increased. As a result, Gürdal, Aras and Katran genotypes were found to be more salt tolerant under NaCl and Na₂SO₄ treatments. Analysis using stress indices showed that it is an effective method to evaluate the tolerance of chickpea genotypes to salt stress. These findings can be used for future chickpea breeding programs and reclamation of saline areas.

Keywords: *Cicer arietinum* L., Genotype, Salinity, Germination, Mineral content, Sodium chloride, Sodium sulfate

1. Introduction

Salinity is a measure of the amount of salt present in soil and water. Salinity is broadly classified as primary and secondary. Primary salinity is the product of natural processes such as erosion, rainfall and strong winds that deposit salt on land and in water over long periods of time (Munns & Tester 2008). Whereas secondary salinity is the effect of anthropogenic activities such as deforestation, land clearing and over-irrigation (Pessarakli & Szabolcs 2016). Saline soil and water are pools of various salts (Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻ and HCO₃⁻). These salts are usually chlorides (NaCl, CaCl₂, MgCl₂), sulfates (Na₂SO₄, MgSO₄), nitrates (NaNO₃, KNO₃), carbonates and bicarbonates (Na₂CO₃, NaHCO₃) and borates. However, the most common salt form is NaCl (Stavi et al. 2021; Pessoa et al. 2022). And sodium chloride (NaCl) constitutes 50-80% of total soluble salts (Rengasamy, 2010). Different chloride salt sources and doses had positive or negative effects on plant growth (Özaktan et.al. 2018). Arid and semi-arid regions face high salt accumulation in soil and water (Arif et al. 2020).

Worldwide, 6% of the total arable land area (about eight million hm² of land) is affected by salt. Thirty percent of arable land is expected to be lost in the next 25 years and 50 percent by the mid-21st century (Ludwig et al. 2018). Increasing electrical conductivity (EC) by more than 4 dSm⁻¹ affects plant growth and is certainly reflected in the quantity and quality of crops in many parts of the world (Abdelaal et al. 2021). An EC of 4 dS m⁻¹ is equivalent to 40 mM NaCl with an osmotic pressure of about 0.2 MPa, an exchangeable sodium percentage (ESP) lower than 15 and a pH higher than 8.5 (Abrol 1986; Sarita et al. 2023).

Salinity is one of the environmental factors that, together with the growing human population, jeopardizes productive agriculture in our world, significantly limiting the production of food crops (Pessoa et al. 2022). Salinity causes significant reductions in the productivity of almost all crop species. Therefore, tackling salinity is crucial to achieve sustainable agricultural

practices and meet current and future food demand globally (Zörb et al. 2019). Salinity has caused a negative impact on morphological and biochemical functions in plants. Salinity inhibits seed germination, plant growth, development and yield (Zhang & Dai, 2019). Salinity inhibits photosynthesis mechanism, transpiration and gas exchange by reducing chlorophyll and carotenoid content, disrupting chloroplast ultrastructure and PSII system, reducing stomatal conductance (Pan et al. 2021). Soil salinity lowers soil water potential and leaf water potential, disrupts plant water relations and reduces plant turgor, which ultimately causes osmotic stress (Navada et al. 2020). Plants take up salts from the soil through transporters that create ion toxicity and disrupt mineral uptake and ion homeostasis. Salinity leads to excessive accumulation of ions (Na^+ and Cl^-) and inhibits K^+ and Ca^{2+} uptake, causing ionic imbalance (Isayenkov & Maathuis 2019). Salinity increases the reactive oxygen species (ROS) content in plant cells and induces oxidative stress. The toxic effects of ROS include lipid peroxidation, membrane disruption, and DNA and protein damage (Ghazali & El Ghazali 2020).

The effects of salt stress on plants vary depending on the type of plant, the type and amount of salt applied and the duration of exposure. In saline environments, plants respond very differently depending on genotypic differences (Naseer et al. 2022). These different growth responses to salinity apply not only to two different plant species but also to different genotypes of the same species (Kumar et al. 2021).

Soil salinity has become one of the most alarming environmental problems in recent decades. With an increasing population to feed and insufficient arable land for cultivation, solving the problem of soil salinity is of great importance. So far, we have mainly two ways to alleviate soil salinization, which are using chemical amendments to restore damaged soil or developing salt-tolerant genotypes.

Legumes are among the most important food groups in the world due to their rich protein, carbohydrate (starch and dietary fiber), vitamin and mineral content (Toklu et al. 2021). Chickpea is one of the first cultivated edible legume plants. Chickpea is the third most widely cultivated edible legume crop in the world after beans and peas. It is a known fact that chickpea cultivation, production and yield have decreased significantly in recent years. Although there are many reasons for this significant decrease in chickpea yield and quality, it is an undeniable fact that the most important of these is due to abiotic factors (drought and salinity) that it faces during growth and development (Sarita et al. 2023).

The objective of this study was to investigate and compare the effects on seed germination, seedling morphology and mineral content of eight chickpea genotypes subjected to different levels of NaCl and Na_2SO_4 salinity stresses using multi-statistical techniques. The further aim was to elucidate the range of variation in salinity tolerance and stress indices among eight chickpea genotypes.

2. Material and Methods

2.1. Material

Ten commercial genotypes of chickpea ('Aras', 'Caner', 'Çiftçi', 'Göksu', 'Gürdal', 'Katrán', 'Nihatbey' and 'Sezgin') were used as plant material in the experiment. Each genotype was characterised by a standard germination test (ISTA 2018) using 4×100 seeds.

2.2. Salinity stress treatments and experimental design

The experiment was conducted at the Edible Legumes Laboratory of the Department of Field Crops in the Research Unit of Erciyes University Faculty of Agriculture in 2021. Seeds were surface-sterilised for 15 min in a 20% commercial bleach (approximately 5 wt% active chlorine), then rinsed three times with distilled water. Salinity stress treatments were created using NaCl and Na_2SO_4 levels with the electrical conductivities of 4, 8, 12 and 16 dS m^{-1} were prepared using the conductivity meter WTW 3.15i before the beginning of the experiment. Distilled water was used as the non-saline control (0 dS m^{-1}). Germination experiments were carried out between 3 pieces of blotting paper of 20×20 cm and incubator at 20 °C. The research was established with 4 replicates and 25 seeds in each replicate. In each replicate, 10 ml of the appropriate test solution was added for each germination paper and placed in sealed plastic bags to prevent evaporation. Seeds were counted at the same time each day and seeds with a rootlet length of 2 mm were considered germinated. This experiment was terminated on the 10th day after sowing when the number of germinated seeds was calculated. No germination was observed in any of the seeds of 'Botan' and 'Onur 01' genotypes at any level of salt application except control. Therefore, no measurements were taken on these genotypes.

2.3. Measurements

Salinity tolerance was measured based on final germination (%), germination energy (%), seedling vigour index on day-10 expressed as the mean of ten randomly selected seeds per replicate (Ellis & Roberts 1980). On the 11th day, Root length (mm), Shoot length (cm), Root fresh weight (mg plant^{-1}), Shoot fresh weight (mg plant^{-1}), Root dry weight (mg plant^{-1}) and Shoot dry weight (mg plant^{-1}) of 10 randomly selected plants were determined with calipers (Özaktan et al. 2018).

2.4. Mineral content

Eight chickpea genotypes were used in the study, but ‘Caner’ and ‘Nihatbey’ genotypes in NaCl salt and ‘Caner’ and ‘Çiftçi’ genotypes in Na₂SO₄ salt at doses of 12 and 16 dS m⁻¹ could not be obtained in sufficient quantities for ICP-OES readings, so these genotypes were not included in the mineral matter readings. Weight measurements were made using a precision balance. Dry weight measurements were obtained by weighing the samples on a precision balance after drying in an oven at 70 °C for 48 hours. The dry weights were crushed in mortars and the mineral matter contents were determined by Agilent 5800 VDV model ICP-OES at 22±2 °C (Mertens 2005).

2.5 Stress index

A total of 16 distinct stress indices were employed to ascertain the tolerance of genotypes to NaCl and Na₂SO₄ stress, with the application of varying doses. The undermentioned stress indices were employed for the purpose of comparing the performance of chickpea genotypes under conditions of salt stress, with a view to identifying those genotypes that exhibited the greatest tolerance.

Y_{pi} = The value of observed feature of each genotypes under normal conditions (control)

Y_{si} = The value of the feature of each genotypes under stressful conditions

Y_p = The mean of the features of the genotypes examined under normal conditions (control)

Y_s = The mean of the features of the genotypes examined under stressful conditions

- Stress Tolerance Index (STI): $= \frac{(Y_{si} \times Y_{pi})}{Y_p^2}$
- Stress Susceptibility Index (SSI): $= \frac{(1 - \frac{Y_{si}}{Y_{pi}})}{SI}$ $SI = 1 - \frac{Y_s}{Y_p}$ (Fischer & Maurer 1978)
- Tolerance (TOL): $= Y_{pi} - Y_{si}$ (Rosielle & Hamblin 1981)
- Superiority index (Pi): $= \sum_{i=1}^n \frac{(Y_{ij} - M_j)^2}{2n}$ i: genotypes, j: environments, M: the highest performing genotypes in the environment j, n: number of location (Clarke et al. 1992; Lin et al. 1986)
- Mean Relative Performance (MRP): $= \left(\frac{Y_{si}}{Y_s} \right) + \left(\frac{Y_{pi}}{Y_p} \right)$ (Hossain et al. 1999)
- Abiotic Tolerance Index (ATI): $= \left(\frac{Y_{pi} - Y_{si}}{\frac{Y_p}{Y_s}} \right) \times \sqrt{Y_{pi} \times Y_{si}}$ (Moosavi et al. 2008)
- Geometric Mean Productivity (GMP): $= \sqrt{Y_{pi} \times Y_{si}}$ (Fernandez 1992)
- Harmonic Mean (HM): $= 2 \times \left(\frac{Y_{pi} \times Y_{si}}{Y_{pi} + Y_{si}} \right)$ (Dadbakhsh et al. 2011)
- Mean Productivity (MP): $= \frac{(Y_{si} + Y_{pi})}{2}$ (Rosielle & Hamblin 1981)
- Reduction (RED): $= \left(\frac{Y_{pi} - Y_{si}}{Y_{pi}} \right) \times 100$ (Farshadfar & Javadinia 2011)

- Relative Decrease in Trait (RDT): $= 100 - \left(\left(\frac{Y_{si}}{100} \right) \times Y_{si} \right)$ (Farshadfar & Elyasi 2012)
- Stress Tolerance Efficiency (STE): $= \left(\frac{Y_{si}}{Y_{pi}} \right) \times 100$ (Fischer & Wood 1981)
- Modified Stress Tolerance Index 1 (MSTI 1): $= \left(\frac{Y_{pi}^2}{Y_p^2} \right) \times STI$ (Farshadfar & Sutka 2002)
- Modified Stress Tolerance Index 2 (MSTI 2): $= \left(\frac{Y_{si}^2}{Y_s^2} \right) \times STI$ (Farshadfar & Sutka 2002)
- Relative Efficiency Index (REI): $= \left(\frac{Y_{si}}{Y_s} \right) \times \left(\frac{Y_{pi}}{Y_p} \right)$ (Hossain et al. 1999)
- Stability Index (SI): $= \left(\frac{Y_{si}}{Y_{pi}} \right)$ (Bousslama & Schapaugh 1984)

The tolerance levels of chickpea genotypes in different stress indices were evaluated using the membership function value (MFV). MFV was calculated using the following equation: $X_i = \frac{X - X_{min}}{X_{max} - X_{min}}$

Where; X_i represents the membership function value of the i trait in a genotype, X_{mean} is the mean of the stress indices value of the i trait in the genotypes, X_{max} and X_{min} are the maximum and minimum values of the stress indices of the i trait observed in all genotypes, respectively. As a result, each trait is assigned an MFV, with values ranging from 0 to 1 (Chen et al. 2012).

Based on a previously outlined approach, the stress tolerance levels of the genotypes were classified into five categories using the mean value (X_{mean}) and standard deviation (SD) of the MFV (Wang et al 2016; Li et al. 2020):

- (1) $X_i \geq X_{mean} + 1.64 \times SD$, high tolerant (HT);
- (2) $X_{mean} + 1.64 \times SD > X_i \geq X_{mean} + 1 \times SD$, tolerant (T);
- (3) $X_{mean} + 1 \times SD > X_i \geq X_{mean} - 1 \times SD$, moderate tolerant (MT);
- (4) $X_{mean} - 1 \times SD > X_i \geq X_{mean} - 1.64 \times SD$, sensitive (S);
- (5) $X_{mean} - 1.64 \times SD > X_i$, high sensitive (HS).

Only high tolerant and tolerant genotypes were evaluated in our study.

2.6 Statistical analysis

Statistical analyses of the data obtained at the end of the research were carried out according to the factorial trial design in random plots with 4 replications and all statistical analyses (Biplot analysis, Scatter plot analysis and correlation analyses) by using JMP Pro 17 package program. Tukey test was used for the difference groupings of the averages (Yuan 2011).

3. Results and Discussion

3.1 Seed germination parameters

Osmotic and ionic stress caused by salt stress disrupts the cellular and metabolic pathways of plants, thus affecting their growth and development (Liang et al. 2018). Seed germination and seedling emergence are fundamental biological processes in the life cycle of a plant and are considered sensitive stages (Munns & Tester 2008). Excellent seed germination and emergence are therefore important for achieving high yields. Therefore, this study investigated the germination characteristics of eight chickpea genotypes under different levels (4, 8, 12 and 16 dS m⁻¹) of NaCl and Na₂SO₄ salt stress.

Eight genotypes showed variability in germination rate in the control treatment and all of the genotypes showed $> 85\%$ germination rate (Aras: 99%, Caner: 89%, Çiftçi: 97%, Gökusu: 92%, Gürdal: 98%, Katran: 97%, Nihatbey: 92% and Sezgin: 100%) (Figure 1). All treatments caused a significant decrease in germination parameters compared to control conditions. The highest salt treatment of NaCl and Na_2SO_4 (16 dS m^{-1}) significantly decreased the germination rate of the genotypes (germination rate: Aras: 55 and 91%, Caner: 21 and 24%, Çiftçi: 77 and 30%, Gökusu: 51 and 90%, Gürdal: 77 and 77%, Katran: 73 and 77%, Nihatbey: 79 and 30% and Sezgin: 62 and 86%, respectively) (Figure 1).



Figure 1- Effect of salinity stress on germination traits of seeds of eight chickpea genotypes subjected to different electrical conductivity levels of NaCl and Na_2SO_4 salts

At the highest salt level of 16 dS m^{-1} , Gürdal and Nihatbey had the highest germination with $\geq 75\%$ in NaCl, while Aras, Gökusu, Gürdal and Sezgin were with ≥ 77 in Na_2SO_4 . Interestingly, Gürdal in NaCl and Aras, Gökusu and Sezgin in Na_2SO_4 were the genotypes with the strongest germination, germination energy and seedling viability index (Figure 1). But, Caner was the most sensitive genotype according to germination parameters in both salt treatments.

Table 1- Mean effect of salinity stress on germination traits of seeds of eight chickpea genotypes by genotype, salt type (NaCl and Na₂SO₄) and level (4, 8, 12 and 16 dS m⁻¹)

<i>Factors</i>	<i>Germination Percentage (%)</i>	<i>Germination Energy (%)</i>	<i>Seedling Viability Index</i>
Genotypes			
Aras	90.8ab	82.8b	556.5cd
Caner	58.0d	47.8f	191.6e
Çiftçi	76.7c	74.5cd	528.6d
Göksu	83.8b	73.1d	517.0d
Gürdal	91.4a	91.4a	827.4a
Katran	79.1c	74.1cd	841.0a
Nihatbey	78.6c	61.6e	597.2c
Sezgin	88.2ab	80.6bc	708.5b
Salts			
NaCl	78.3b	68.8b	610.7a
Na ₂ SO ₄	83.8a	77.6a	581.2b
Doses			
Control	95.9a	93.2a	1103.2a
4 dS m ⁻¹	90.6b	81.5b	763.2b
8 dS m ⁻¹	81.8c	73.8c	575.6c
12 dS m ⁻¹	74.3d	64.0d	344.6d
16 dS m ⁻¹	62.5e	53.5e	193.1e
Analysis of Variance			
Genotypes	**	**	**
Salts	**	**	*
Doses	**	**	**

Means indicated with the same letters in the same column are not significantly different ($P < 0.05$): *; $P < 0.05$, **: $P < 0.01$

Statistical analyses of the mean values of the examined factors were made and presented in Table 1 ($P < 0.05$ or 0.01). Germination parameters showed a negative relationship with the different levels of both salt treatments. All genotypes were more sensitive to NaCl treatment than Na₂SO₄ in terms of germination and germination energy, while seedling vigour index was higher. Similarly, Toderich et al. (2020) reported that for *Chenopodium quinoa*, NaCl salinity significantly reduced the germination rate, unlike Na₂SO₄. Also, Assareh et al (2010) reported that for *Halostachys caspica* C.A.Mey, germination parameters were more sensitive to NaCl than to Na₂SO₄, but growth was more sensitive to Na₂SO₄ than to NaCl. The toxic effect of Na₂SO₄ on seedling vigour index and growth may be caused by preventing the uptake of nutrients necessary for plant development, which causes nutrient imbalance and toxicity in cells (K Abass Al-Hamzawi, 2007; Reich et al. 2018; Voisin et al. 2019). Among the genotypes, Gürdal was more tolerant in terms of germination (91.4%), germination energy (91.4%) and seedling vigour rate (827.4%), whereas Caner was the most sensitive genotype (58.0%, 47.8% and 191.6%, respectively).

Increased salt concentrations in soil or water negatively affect the germination process (Anuradha & Seeta Ram Rao 2001; Laghmouchi et al. 2017). In this study, germination percentage was delayed or restricted under salinity stress compared to control growth conditions. The observed reduction in germination rate under salinity stress could be attributed to salt toxicity and changes in cellular osmotic potential. During germination under salt stress, seeds require higher water uptake due to the accumulation of soluble solutes around the seeds, resulting in an increase in osmotic pressure (Iqbal et al. 2020). This results in excessive uptake of ions causing ion toxicity in the plant, reducing the water potential gradient between external environments and inhibiting seed

primary root emergence (Dehnavi et al. 2020; del Carmen Martínez-Ballesta et al. 2020). Declining trends in germination values of chickpea genotypes were observed with increasing salinity level. This finding is in accordance with previous studies conducted under saline conditions in chickpea (Joshi et al. 2024; Lavrenko et al. 2019), quinoa (Causin et al. 2020), finger millet (Mukami et al. 2020), lettuce (Ahmed et al. 2019), alfalfa (Sandhu et al. 2017) and wheat (Tounsi et al. 2017). Under higher salt concentration, the reduction in germination rate for the salinity tolerant genotype (Gürdal) was less compared to most of the salt sensitive genotypes (Caner).

3.2 Morphological parameters

There was some variation in the morphological parameters of the eight genotypes of chickpea under salt stress. The eight genotypes showed variability in root and shoot growth parameters in the control treatment, with Katran showing the tallest root length with 109.4 mm (Figure 2) and Gürdal and Katran showing the tallest shoot length with 84.1 and 81.6 mm, respectively (Figure 3). Further increases in salinity resulted in decreases in root and shoot growth parameters for all genotypes.

In high salinity treatments, in NaCl salt, Gürdal and Nihatbey had the highest root length (45.6 and 29.4 mm), root fresh weight (1085.3 and 1018.3 mg plant⁻¹) and root dry weight (67.3 and 72.5 mg plant⁻¹), but in Na₂SO₄ salt, Katran had the longest root length (29.5 mm) while Aras had the highest root fresh weight (1018.3 mg plant⁻¹) and root dry weight (69.5 mg plant⁻¹) (Figure 2).



Figure 2- Effect of salinity stress on root growth parameters of seeds of eight chickpea genotypes subjected to different electrical conductivity levels of NaCl and Na₂SO₄ salts

Shoot length of all genotypes decreased with increasing salinity level (Figure 3). The longest shoots were recorded Gürdal (26 cm) at the highest NaCl treatment and Katran (14.3 cm) at the highest Na_2SO_4 treatment. Surprisingly, in 16 dS m^{-1} treatment, Nihatbey showed the highest shoot fresh weight ($1155.5 \text{ mg plant}^{-1}$) and shoot dry weight ($101.3 \text{ mg plant}^{-1}$) for NaCl salt. In contrast, Nihatbey was the most sensitive genotype in all shoot growth parameters in 16 dS m^{-1} treatment of Na_2SO_4 , and Çiftçi showed a similar trend. In fact, their values were measured at almost zero (Figure 3). Generally, it can be attributed that solutions containing SO_4^{2-} anions have significantly greater toxicity than Cl^- solutions at iso-osmotic concentrations (Voisin et al. 2019). However, the mechanism of effect of salt types and concentrations on plant germination and development has not been fully explained. Because plant species and genotypes vary in their sensitivity and resistance to salt types (Iqbal 2003; Peterson & Murphy 2015; Dadshani et al. 2019; Kurunc et al. 2020)



Figure 3- Effect of salinity stress on shoot growth parameters of seeds of eight chickpea genotypes subjected to different electrical conductivity levels of NaCl and Na_2SO_4 salts

Statistical analysis on the mean data of the examined factors that differences among genotypes, salts and doses were significant for the growth and development parameters root length, root fresh weight, root dry weight, shoot length, shoot fresh weight, shoot dry weight ($P < 0.05$ or 0.01 ; Table 2). Plant growth showed a negative relationship with the different level of salt stress applied. A gradual decrease in plant growth and development parameters of eight genotypes in all treatments of NaCl and Na_2SO_4 ($4, 8, 12$ and 16 dS m^{-1}) compared to control. Moreover, a high reduction in growth parameters of all genotypes was recorded at 16 dS m^{-1} .

Table 2- Mean effect of salinity stress on root and shoot growth parameters of eight chickpea genotypes by genotype, salt type (NaCl and Na₂SO₄) and level (4, 8, 12 and 16 dS m⁻¹)

<i>Factors</i>	<i>Root length (mm)</i>	<i>Root fresh weight (mg plant⁻¹)</i>	<i>Root dry weight (mg plant⁻¹)</i>	<i>Shoot length (cm)</i>	<i>Shoot fresh weight (mg plant⁻¹)</i>	<i>Shoot dry weight (mg plant⁻¹)</i>
Genotypes						
Aras	34.7e	1462.2b	94.6b	23.8e	1359.9cd	84.6c
Caner	34.7e	523.3d	39.8e	9.8f	608.6e	47.5d
Çiftçi	16.9f	970.2c	60.9d	22.9e	1177.8d	83.9c
Göksu	38.4d	1293.6bc	79.9c	21.8e	1284.6cd	96.4c
Gürdal	34.7e	1868.5a	98.1b	39.0b	2075.1a	117.1b
Katran	49.3b	1597.9ab	95.4b	43.3a	2075.7a	155.3a
Nihatbey	57.8a	1349.5b	91.9b	29.2d	1586.1b	121.7b
Sezgin	40.1c	1466.3b	115.8a	32.0c	1464.3bc	128.5b
Salts						
NaCl	41.2a	1283.1b	79.4b	29.7a	1443.9b	106.6a
Na ₂ SO ₄	37.9b	1349.8a	89.7a	25.8b	1464.1a	102.1b
Doses						
Control	62.3a	2145.9a	146.8a	51.8a	2463.4a	178.5a
4 dS m ⁻¹	47.5b	1699.4b	96.8b	35.7b	1855.5b	122.1b
8 dS m ⁻¹	42.0c	1374.1c	83.9c	26.8c	1587.1c	110.4c
12 dS m ⁻¹	28.9d	884.1d	61.5d	15.7d	888.4d	71.5d
16 dS m ⁻¹	16.9e	478.7e	33.7e	8.6e	475.7e	39.2e
Analysis of Variance						
Genotypes	**	**	**	**	**	**
Salts	**	*	**	**	*	*
Doses	**	**	**	**	**	**

Means indicated with the same letters in the same column are not significantly different ($P < 0.05$). *: $P < 0.05$, **: $P < 0.01$

Under salt stress, the highest root length was found in Nihatbey with 57.8 mm and the lowest in Çiftçi with 16.9 mm. The highest root fresh weight and dry weight were observed in Gürdal and Sezgin genotypes, respectively.

As salinity level increased, shoot length, shoot fresh weight and shoot dry weight of all genotypes decreased (Table 2). The longest shoot was observed in Katran with 43.3 cm, followed by Gürdal genotype with 39.0 cm. These genotypes also had high data in terms of shoot fresh weight and shoot dry weight. The lowest shoot growth parameters were recorded in Caner genotype. In general, Gürdal, Katran, Nihatbey and Sezgin were found to be salt tolerant for the growth parameters examined compared to other genotypes.

Among the salt genotypes, Na₂SO₄ had higher inhibitory effect on root length, shoot length and shoot dry weight, while NaCl had higher inhibitory effect on root fresh weight, root dry weight and shoot fresh weight.

Salinity negatively affects germination and early stages of growth in chickpea (Kundu et al. 2023). Several studies have been conducted to understand the complexities of chickpea salinity tolerance from both physiological and genetic perspectives (Atieno et al. 2017; Kotula et al. 2019; Pushpavalli et al. 2015). Some recent studies have identified some chickpea genotypes that can withstand higher salinity up to EC 9 dSm⁻¹ (Kaur et al. 2022; Mann, A. et al. 2019). In this study, similarly, some genotypes

(Çiftçi, Gürdal, Katran, Nihatbey, Sezgin for NaCl and Aras, Gürdal, Katran for Na₂SO₄) were tolerant to salt treatments at 8 dSm⁻¹ concentration.

3.3 Mineral content

The mean values and statistical effects of sodium chloride and sodium sulfate salts on germination mineral content of different chickpea genotypes are given in Table 3. The effects of genotype, salt and dose among the sources of variation on the examined mineral contents were found statistically significant at 1% level.

Table 3- Mean macronutrient (Na, K, Ca, Mg, S) concentrations (ppm) and Na/K rate by genotype, salt type (NaCl and Na₂SO₄) and level (4, 8, 12 and 16 dS m⁻¹)

Factors	Na	K	Na/K	Ca	Mg	S
Genotypes						
Aras	4710.6a	19478.4b	0.241b	2374.7a	758.0b	4060.1a
Göksu	3682.0c	21765.8a	0.164d	1118.2d	735.2bc	3423.7b
Gürdal	3816.1c	19317.7b	0.194c	1489.1b	815.6a	2778.9d
Katran	4230.0b	16497.6c	0.252a	1330.5c	703.5d	2961.0c
Sezgin	3030.9d	18975.9b	0.152e	947.5e	723.4cd	2368.8e
Stress						
NaCl	4015.1a	20822.2a	0.190b	1918.7a	819.7a	1693.6b
Na ₂ SO ₄	3772.7b	17591.9b	0.211a	985.3b	674.6b	4543.4a
Doses						
Control	828.0e	16131d	0.052e	1132.0b	775.2b	1523.5e
4 dS m ⁻¹	2278.2d	18616.3c	0.126d	1212.5b	688.9c	2387.7d
8 dS m ⁻¹	3345.2c	19857.5b	0.200c	1503.6ab	698.2c	3083.0c
12 dS m ⁻¹	5267.4b	21050.1a	0.260b	1536.8ab	700.6c	3731.2b
16 dS m ⁻¹	7250.6a	20380.4b	0.365a	1875.2a	872.8a	4867.1a
Analysis of Variance						
Genotypes	**	**	**	**	**	**
Salts	**	**	**	**	**	**
Doses	**	**	**	**	**	**

Means indicated with the same letters in the same column are not significantly different ($P < 0.05$) *: $P < 0.05$, **: $P < 0.01$

It is important to determine Na, K and Na:K ratio to understand the salt tolerance mechanism (Zeeshan et al. 2020). When Table 3 is analyzed, sodium, Ca and S contents were the highest in Aras genotype with 4710.6, 2374.7 and 4060.1 ppm, respectively, while Sezgin genotype had the lowest content with 3030.9, 947.5 and 2368.8 ppm, respectively.

When the average of the doses was analyzed, Na (828.0-7250.6 ppm), Na/K (0.052-0.365), Ca (1132-1875.2 ppm) and S (1523.5-4867.1 ppm) contents increased as the doses increased (0, 4, 8, 12 and 16 dS m⁻¹). Irik & Bikmaz (2024) reported that Na:K ratio increased as NaCl doses increased. While the lowest K content was 16131 ppm in the control group, the highest content was obtained as 21050.1 ppm at 12 dS m⁻¹ dose and 20380.4 ppm at 16 dS m⁻¹ dose. The highest Mg content was obtained at 16 dS m⁻¹ dose (872.8 ppm) and the lowest was obtained from the control (775.2 ppm) treatment average.

3.4 Biplot and scatter plot analysis

The output of the biplot analysis on the parameters examined in the study is given in Figures 4 and 5. The line of agreement between the parameters examined and the correlation relationship between the scatter of the genotypes and each other are given in Figure 6. In Figure 6, the red colored circles represent the positive relationship between the two parameters and the blue colored circles represent the negative relationship, while the increase in the diameter of the circle indicates that the correlation value is high (Okumuş et al. 2023). In the biplot analysis including agro-morphological parameters, genotypes, salts and doses, 10 independent principal component axes were obtained. The eigenvalues of the first two principal components, which accounted for 83.706% of the total variation, were recorded as 7.272 and 1.098, respectively. In the light of these data, it is stated that the biplot analysis can be interpreted successfully (Özaktan et al. 2022). In addition, the lengths, positions and angle values of the axes formed as a result of biplot analysis reveal the negative or positive relationship between the principal component axes (Ozaktan et al. 2023). When the angle between GP and GE, which have approximately the same axis length and are located in the same region, is evaluated, it is determined that there is a highly positive relationship ($r=0.872$). SDW, SFW, SL, RDW, RFW and SVI parameters located in the same region have a positive relationship with each other. Especially when the angle between

the RL axis length and the resulting angle is taken into consideration, there is a high positive correlation between RL and SL ($r=0.932$), SDW ($r=0.910$) and SVI ($r=0.964$) parameters. The fact that the MGT parameter alone is located in a different region (high angle value) shows that it is negatively correlated with the other parameters. In particular, the correlation value between it and GE was calculated as $r=-0.557$ (Figure 4 and 5.). The findings obtained are in parallel with the results reported by İrik & Bıkmaz (2024).

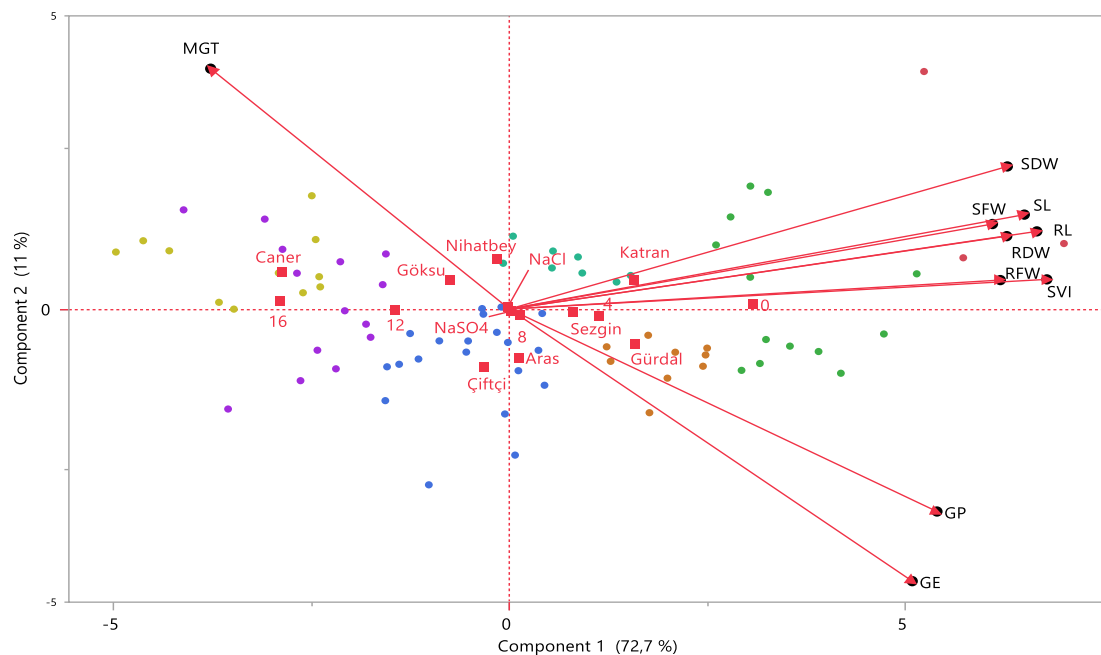


Figure 4- Biplot analysis on the studied agro-morphological parameters of chickpea genotypes. (RL, root length; SL, shoot length; RFW, root fresh weight; SWF, shoot fresh weight; RDW, root dry weight; SDW, shoot dry weight; MGT, mean germination time; GP, germination percentage; GE, Germination Energy; SVI, seedling viability index)

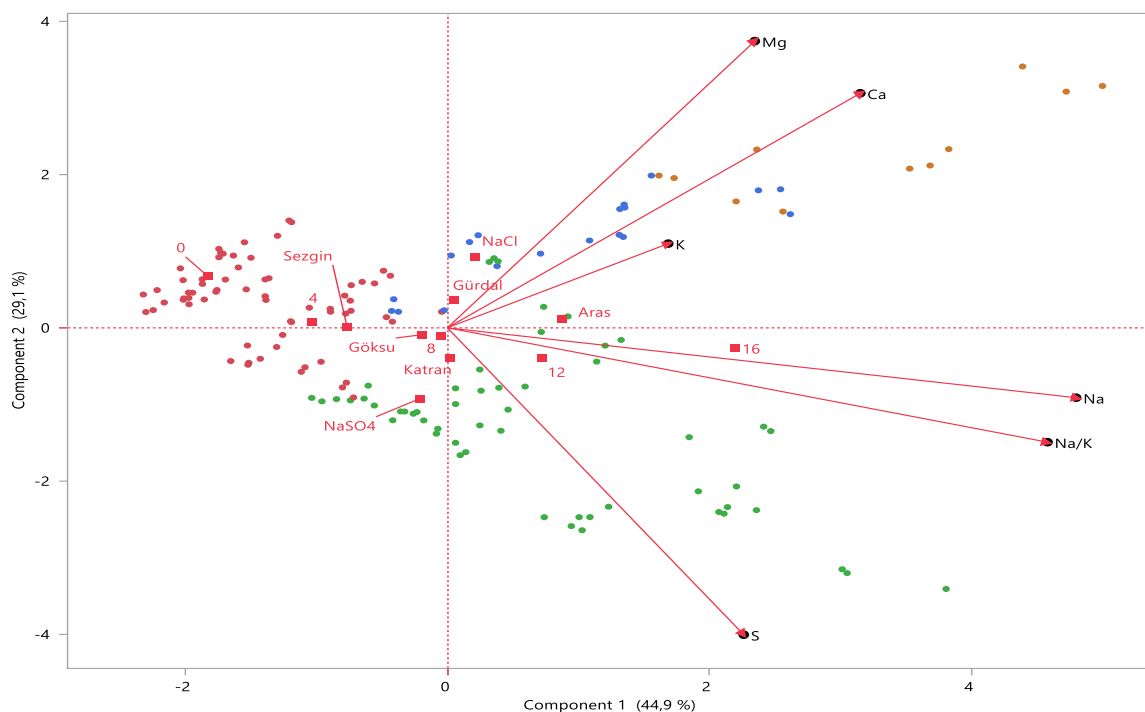


Figure 5- Biplot analysis for the analyzed mineral matter contents (Na, K, Na/K, Ca, Mg, S) of chickpea genotypes

As a result of the biplot analysis in which the mineral matter contents of chickpea genotypes treated with sodium chloride and sodium sulfate salts were evaluated together, 6 independent principal component axes were obtained. The eigenvalues of the first two principal components, which accounted for 74.009% of the total variation, were recorded as 2.697 and 1.744, respectively. These results show that the biplot analysis can be interpreted successfully (Ozaktan & Doymaz 2022). Based on

the positions, lengths and angles of the axes, Ca element is positively correlated with Mg element ($r=0.660$), Na element has a high positive correlation value with Na/K ($r=0.949$) and a positive correlation with S element ($r=0.509$) (Figures 4 and 5).

Calcium plays an important role in many physiological and cellular events such as cell walls and membrane structure (Nayyar 2003; Knight & Knight 2001). In addition, it competes with Na content and an increase in Na content decreases Ca binding (Zehra et. al. 2012).

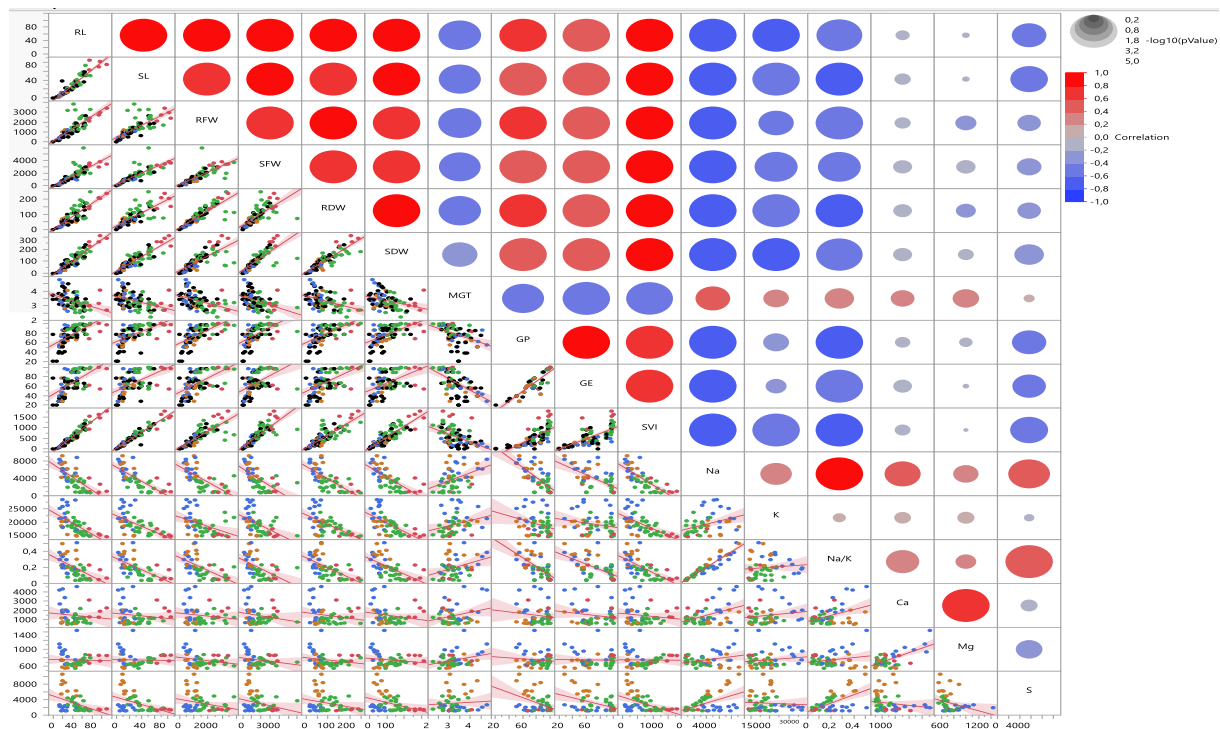


Figure 6- Scatter plot and matrix for overview of correlations and fit lines. RL, root length; SL, shoot length; RFW, root fresh weight; SFW, shoot fresh weight; RDW, root dry weight; SDW, shoot dry weight; MGT, mean germination time; GP, germination percentage; GE, Germination Energy; SVI, seedling viability index; Na, sodium; K, potassium; Na/K, sodium/potassium; Ca, calcium; Mg, magnesium; S, sulfur

3.5 Stress indices

The germination performance of chickpea genotypes under different concentrations of NaCl and Na₂SO₄ stress was evaluated using 16 different stress indices (STI, SSI, TOL, Pi, MRP, ATI, GMP, HM, MP, Red, RDT, STE, MSTI1, MSTI2, REI, and SI). These indices were calculated based on the average values of parameters critical during the germination process, such as root length, shoot length, root dry weight, and shoot dry weight. The membership function value (MFV) was then calculated to analyze these indices. As a result of this analysis, the tolerance levels of chickpea genotypes against NaCl and Na₂SO₄ salt stress were determined. Table 4 present the chickpea genotypes that were classified as tolerant and highly tolerant based on the parameters examined under stress conditions.

Root length: Under NaCl stress, the Katran (as indicated by the STI, TOL, GMP, MP, MSTI 1, MSTI 2, and REI indices) and the Gürdal genotype (as indicated by the SSI, Pi, MRP, HM, Red, RTE, STE, and SI indices) consistently exhibited high tolerance across most stress indices, indicating robust resistance in terms of root length. Similarly, the Nihatbey the Çiftçi and the Sezgin varieties showed tolerant and high tolerant responses in specific indices (STI, SSI, ATI, Red and SI), which indicates a relatively lower performance reduction. (Table 4). Under Na₂SO₄ stress, Katran again demonstrated high tolerant responses across multiple indices, reflecting its strong ability to maintain root length under sulfate-induced stress. Additionally, Sezgin, Nihatbey and Caner exhibited high tolerance in selected indices, whereas others like, Çiftci and Onur were categorized in the tolerant range.

Shoot length: The Gürdal was identified as highly tolerant in several stress indices (SSI, TOL, Pi, MRP, ATI, GMP, HM, MP, RDT, MSTI 1, MSTI 2 and REI), exhibiting significant resilience in shoot length under NaCl stress. Katran also showed strong tolerance in the STI, TOL, Pi, MRP, GMP, HM, MP, Red, RDT, STE, MSTI 2 and SI indices, indicating considerable resistance in shoot length under similar conditions (Table 4). In the case of Na₂SO₄ stress, Katran remained highly tolerant across multiple indices, suggesting its high tolerance to Na₂SO₄ stress in shoot length. Caner and Nihatbey also showed strong tolerance in some indices (Table 4).

Root dry weight: The Katran was classified as high tolerant across multiple indices, including STI, TOL, Pi, MRP, GMP, HM, MP, RDT, MSTI 1, MSTI 2 and REI demonstrating notable resilience in root dry weight under NaCl stress. In contrast, Nihatbey also demonstrated high tolerant responses in selected indices, though less consistently than Katran. (Table 4). Under Na₂SO₄ stress, Sezgin was identified as highly tolerant across many stress indices (STI, Pi, MRP, ATI, GMP, HM, MP), indicating its high resistance in root dry weight. Katran and Aras also displayed high tolerance in several indices, including STE, MSTI 1, MSTI 2, REI and SI (Table 4).

Table 4- The tolerant chickpea genotypes according to stress indexes for NaCl and Na₂SO₄ salts during early growth stage

Stress Indices	NaCl				Na ₂ SO ₄			
	Root Length	Shoot Length	Root Dry Weight	Shoot Dry Weight	Root Length	Shoot Length	Root Dry Weight	Shoot Dry Weight
STI	Katran ^a Çiftçi ^b	Katran ^a Çiftçi ^b	Katran ^a Çiftçi ^b	Katran ^a Çiftçi ^b	Katran ^a	Katran ^a	Sezgin ^a Aras ^b	Göksu ^b Onur ^b
SSI	Gürdal ^a Nihatbey ^b	Gürdal ^a Nihatbey ^b	Gürdal ^a Nihatbey ^b	Gürdal ^a Nihatbey ^b	Nihatbey ^a Katran ^b	Nihatbey ^a Caner ^b	Katran ^a Botan ^b	Nihatbey ^b Botan ^b Sezgin ^b
TOL	Katran ^a	Gürdal ^a Katran ^a	Katran ^a Nihatbey ^b	Gürdal ^b Katran ^b	Katran ^b	Nihatbey ^a Aras ^b	Sezgin ^b Aras ^b	Göksu ^b Onur ^b
Pi	Gürdal ^b Katran ^b	Gürdal ^b Katran ^b	Katran ^b Nihatbey ^b	Katran ^b	Katran ^b	Katran ^b	Sezgin ^b Aras ^b	Göksu ^b Onur ^b Sezgin ^b
MRP	Gürdal ^a Katran ^a	Gürdal ^a Katran ^a	Katran ^b Nihatbey ^b	Katran ^b Nihatbey ^b	Katran ^b	Katran ^a	Sezgin ^b Aras ^b	Göksu ^b Onur ^b Sezgin ^b
ATI	Sezgin ^a Katran ^b	Gürdal ^a	Sezgin ^a Katran ^b	Sezgin ^a Gürdal ^b Nihatbey ^b	Sezgin ^a Göksu ^b	Katran ^b	Sezgin ^b	Onur ^a
GMP	Katran ^a	Gürdal ^b Katran ^b	Katran ^a	Katran ^a	Katran ^b	Katran ^a	Sezgin ^a Aras ^b	Onur ^b Göksu ^b
HM	Gürdal ^b Katran ^b	Gürdal ^b Katran ^b	Katran ^b Nihatbey ^b	Katran ^b Nihatbey ^b	Katran ^a	Katran ^a	Sezgin ^b Aras ^b	Göksu ^b Onur ^b Sezgin ^b
MP	Katran ^b	Gürdal ^b Katran ^b	Katran ^b	Katran ^b	Katran ^b	Katran ^a	Sezgin ^a Aras ^b	Göksu ^b Onur ^b
Red	Gürdal ^a Nihatbey ^b	Nihatbey ^a Gürdal ^b Katran ^b	Nihatbey ^a	Çiftçi ^a	Sezgin ^a Çiftçi ^b	Onur ^b	Caner ^b Çiftçi ^b Sezgin ^b	Aras ^b Caner ^b Çiftçi ^b
RDT	Gürdal ^a Katran ^b	Gürdal ^a Katran ^b	Katran ^a Nihatbey ^b	Katran ^a	Caner ^a Onur ^b	Caner ^b	Caner ^b Çiftçi ^b Katran ^b	Caner ^b Çiftçi ^b
STE	Gürdal ^a	Nihatbey ^a Gürdal ^b Katran ^b	Nihatbey ^a	Çiftçi ^a	Katran ^a	Caner ^a	Katran ^a Botan ^b	Botan ^b Sezgin ^b
MSTI 1	Katran ^a	Gürdal ^a	Katran ^a	Katran ^a	Katran ^b Sezgin ^b	Katran ^a	Sezgin ^a	Onur ^a Göksu
MSTI 2	Katran ^a Gürdal ^b	Gürdal ^a Katran ^a	Katran ^a Nihatbey ^b	Katran ^a	Katran ^a	Katran ^a	Aras ^a Sezgin ^b	Göksu ^b Onur ^b Sezgin ^b
REI	Katran ^a Gürdal ^b	Gürdal ^a Katran ^a	Katran ^a Nihatbey ^b	Katran ^a Nihatbey ^b	Katran ^a	Katran ^a	Sezgin ^a Aras ^b	Göksu ^b Onur ^b Sezgin ^b
SI	Gürdal ^a Nihatbey ^b	Nihatbey ^a Gürdal ^b Katran ^b	Nihatbey ^b	Çiftçi ^a	Katran ^b	Caner ^a	Katran ^a Botan ^b	Botan ^b Sezgin ^b

^a: high tolerant, ^b: tolerant. STI, stress tolerance index; SSI, stress susceptibility index; TOL, tolerance; Pi, superiority index; MRP, mean relative performance; ATI, abiotic tolerance index; GMP, geometric mean productivity; HM, harmonic mean; MP, mean productivity; Red, Reduction; RDT, relative decrease in trait; STE, Stress tolerance efficiency; MSTI 1, modified stress tolerance index 1; MSTI 2, modified stress tolerance index 2; REI, relative efficiency index; SI, stability index

Shoot dry weight: Katran exhibited strong resilience in shoot dry weight under NaCl stress, being classified as highly tolerant across multiple indices such as STI, GMP, HM, MP, MSTI 1, MSTI 2 and REI. Çiftçi, on the other hand, was categorized as tolerant according to the STI, Red, STE, and SI indices, showing notable resistance, particularly in shoot dry weight under stress conditions (Table 4). In response to Na₂SO₄ stress, Göksu and Onur were highly tolerant across many indices (STI, TOL, Pi,

MRP, ATI, GMP, HM, MP, MSTI 1 and MSTI 2), indicating significant resistance in shoot dry weight. Sezgin also demonstrated high tolerance to Na₂SO₄ stress (Table 4).

As illustrated in Table 4, Katran exhibited remarkable performance under both NaCl and Na₂SO₄ stress, demonstrating high tolerance across root and shoot parameters in both conditions. Gürdal displayed robust resilience, particularly in terms of shoot length and dry weight under conditions of NaCl stress. Similarly, Sezgin demonstrated notable tolerance to Na₂SO₄ stress, particularly in terms of root dry weight. Furthermore, Göksu and Onur exhibited notable resilience in shoot dry weight under Na₂SO₄ stress. While Nihatbey and Çiftçi demonstrated high tolerance in specific parameters, namely Nihatbey in root-related traits and Çiftçi in shoot dry weight, the overall tolerance of Nihatbey and Caner to Na₂SO₄ stress appeared more limited in comparison to other genotypes.

The stress indices used in this study have proven to be reliable selection criteria in assessing tolerance to abiotic stress, particularly salinity. These indices have been successfully applied in similar research on various crops, including chickpeas, to evaluate their performance under stress conditions. Our results are consistent with previous studies, which have also highlighted the effectiveness of these indices in identifying tolerant genotypes (Farshadfar and Javadinia 2011; Chen 2012; Meena et al. 2014; Bennani et al. 2017; Khan et al. 2018; Lamba et al. 2023). The alignment of our findings with earlier research further validates the use of stress indices in screening crop genotypes for stress resilience. Therefore, these indices can be considered valuable tools for future breeding programs aimed at improving stress tolerance in chickpea and other crops.

4. Conclusions

This study investigated the germination, growth, and mineral content of eight chickpea genotypes under varying levels of NaCl and Na₂SO₄ salt stress. The findings revealed that salt stress significantly impeded germination, growth, and mineral uptake in all genotypes. However, the genotypes exhibited varying degrees of tolerance, with Gürdal, Aras, and Katran demonstrating superior resilience to salt stress.

The study highlighted the importance of stress indices as reliable tools for assessing salt tolerance in chickpea. Indices such as STI, SSI, TOL, Pi, MRP, ATI, GMP, HM, MP, Red, RDT, STE, MSTI1, MSTI2, REI, and SI accurately identified tolerant genotypes. The Katran genotype consistently displayed high tolerance across multiple indices, indicating its exceptional resilience to salt stress. Other genotypes, such as Gürdal, Sezgin, Göksu, and Onur, also demonstrated notable tolerance to specific parameters.

Furthermore, the study underscored the role of mineral content in salt tolerance. Potassium, sodium, sulfur, and the sodium/potassium ratio were observed to increase with rising salt concentrations. The ability of tolerant genotypes to maintain favorable mineral balances, particularly the Na/K ratio, contributed to their superior performance under salt stress.

In conclusion, this research provides valuable insights into the salt tolerance mechanisms of chickpea genotypes. The identified tolerant genotypes offer promising potential for breeding programs aimed at developing salt-resistant chickpea genotypes. Future studies could explore the underlying physiological and genetic mechanisms governing salt tolerance in these genotypes, further enhancing our understanding of chickpea resilience to salinity stress.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Abdelaal S M S, Moussa K F, Ibrahim A H, Mohamed E S, Kucher D E, Savin I & Abdel-Fattah M K (2021). Mapping Spatial Management Zones of Salt-Affected Soils in Arid Region: A Case Study in the East of the Nile Delta, Egypt. *Agronomy* 11(12): 2510. <https://doi.org/10.3390/AGRONOMY11122510>
- Abrol I (1986). Salt-affected soils: problems and prospects in developing countries. CAB Digital Library. <https://www.cabidigitallibrary.org/doi/full/10.5555/19881923285>
- Ahmed S, Ahmed S, Roy S K, Woo S H, Sonawane K D & Shohael A M (2019). Effect of salinity on the morphological, physiological and biochemical properties of lettuce (*Lactuca sativa* L.) in Bangladesh. *Open Agriculture* 4(1): 361–373. <https://doi.org/10.1515/OPAG-2019-0033/HTML>
- Anuradha S & Seeta Ram Rao S (2001). Effect of brassinosteroids on salinity stress induced inhibition of seed germination and seedling growth of rice (*Oryza sativa* L.). *Plant Growth Regulation* 33(2): 151–153. <https://doi.org/10.1023/A:1017590108484>

- Arif Y, Singh P, Siddiqui H, Bajguz A & Hayat S (2020). Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. *Plant Physiology and Biochemistry* 156: 64–77. <https://doi.org/10.1016/J.PLAPHY.2020.08.042>
- Assareh M H, Rasouli B & Amiri B (2010). Effects of NaCl and Na₂SO₄ on germination and initial growth phase of *Halostachys caspica*. *Desert* 15: 119–125
- Atieno J, Li Y, Langridge P, Dowling K, Brien C, Berger B, Varshney R K & Sutton T (2017). Exploring genetic variation for salinity tolerance in chickpea using image-based phenotyping. *Scientific Reports* 7(1): 1–11. <https://doi.org/10.1038/s41598-017-01211-7>
- Bousslama M & Schapaugh W T (1984). Stress tolerance in soybean, part 1: Evaluation of three screening techniques for heat and drought tolerance. *Crop Science* 24(5): 933–937. <https://doi.org/10.2135/cropsci1984.0011183X002400050026x>
- Causin H F, Bordón D A E & Burrieza H (2020). Salinity tolerance mechanisms during germination and early seedling growth in *Chenopodium quinoa* Wild. genotypes with different sensitivity to saline stress. *Environmental and Experimental Botany*, 172, 103995. <https://doi.org/10.1016/J.ENVEXPBOT.2020.103995>
- Chen X J, Min D H, Yasir T A & Hu Y G (2012). Evaluation of 14 morphological, yield-related and physiological traits as indicators of drought tolerance in Chinese winter bread wheat revealed by analysis of the membership function value of drought tolerance (MFVD). *Field Crops Research* 137: 195–201
- Clarke J M, De Pauw R M & Townley-Smith T M (1992). Evaluation of methods for quantification of drought tolerance in wheat. *Crop Science* 32: 732–737
- Dadbakhsh A, Yazdansepar A & Ahmadizadeh M (2011). Study drought stress on yield of wheat (*Triticum aestivum* L.) genotypes by drought tolerance indices. *Advances in Environmental Biology* 5(7): 1804–1810
- Dadshani S, Sharma R C, Baum M, Ogbonnaya F C, León J & Ballvora A (2019). Buğdayda tuz stresine tepkinin çok boyutlu değerlendirmesi. *PLoS One*, 14(9), e0222659.
- Dehnavi A R, Zahedi M, Ludwiczak A, Perez S C & Piernik A (2020). Effect of Salinity on Seed Germination and Seedling Development of Sorghum (*Sorghum bicolor* (L.) Moench) Genotypes. *Agronomy* 10(6): 859. <https://doi.org/10.3390/AGRONOMY10060859>
- del Carmen Martínez-Ballesta M, Egea-Gilabert C, Conesa E, Ochoa J, Vicente M J, Franco J A, Bañon S, Martínez J J & Fernández J A (2020). The Importance of Ion Homeostasis and Nutrient Status in Seed Development and Germination. *Agronomy* 10(4): 504. <https://doi.org/10.3390/AGRONOMY10040504>
- Farshadfar E & Elyasi P (2012). Screening quantitative indicators of drought tolerance in bread wheat (*Triticum aestivum*) landraces. *European Journal of Experimental Biology* 2(3): 577–584
- Farshadfar E & Javadinia J (2011). Evaluation of chickpea (*Cicer arietinum* L.) genotypes for drought tolerance. *Seed and Plant Improvement Journal* 27(4): 517–537
- Farshadfar E & Sutka J (2002). Multivariate analysis of drought tolerance in wheat substitution lines. *Cereal Research Communications* 31: 33–39
- Fernandez G C J (1992). Effective selection criteria for assessing plant stress tolerance. In Kuo C G (Ed.), *Adaptation of Food Crops to Temperature and Water Stress* (pp. 257–270). International Symposium, Taiwan.
- Fischer K S & Wood G (1981). Breeding and selection for drought tolerance in tropical maize. Symposium on Principles and Methods in Crop Improvement for Drought Resistance with Emphasis on Rice, IRRI, Philippines.
- Fischer R A & Maurer R (1978). Drought resistance in spring wheat cultivars. *Australian Journal of Agricultural Research* 29: 897–912
- Ghazali G E B (2020). Suaeda vermiculata Forssk. ex J.F. Gmel.: Structural Characteristics and Adaptations to Salinity and Drought: A Review. *International Journal of Scientific & Engineering Research*. <https://doi.org/10.18483/ijsc.2268>
- Hossain A B S, Sears A G, Cox T S & Paulsen G M (1999). Desiccation tolerance and its relationship to assimilate partitioning in winter wheat. *Crop Science* 30: 622–627
- Iqbal R M (2003). NaCl ve Na altında yetiştirilen buğdayın yaprak alanı ve iyon içeriği. *Pakistan Journal of Biological Sciences* 6: 1512–1514
- Iqbal S, Hussain S, Qayyum M et al. (2020). The response of maize physiology under salinity stress and its coping strategies. In Akbar Hossain (Ed.), *Plant Stress Physiology*. IntechOpen.
- Isayenkov S V & Maathuis F J M (2019). Plant salinity stress: Many unanswered questions remain. *Frontiers in Plant Science*, 10, 80. <https://doi.org/10.3389/fpls.2019.00080>
- Joshi J & Kavane A (2024). Estimation of salinity stress tolerant level of chickpea cultivars (*Cicer arietinum*) using seed germination experiment followed by good agricultural practices. *Springer Journal of Botany* 37(1): 421–425. <https://doi.org/10.1007/s42535-023-00579-4>
- K Abass Al-Hamzawi, M. (2007). Effect of sodium chloride and sodium sulfate on growth, and ions content in faba-bean (*Vicia faba*). *J Kerbala Univ* 3(2): 152-163
- Kaur G, Sanwal S, Sehrawat N, Kumar A, Kumar N & Mann A (2022). Assessing the effect of salinity stress on root and shoot physiology of chickpea genotypes using hydroponic technique. *Indian Journal of Genetics and Plant Breeding* 81(4): 92–95. <https://doi.org/10.31742/ISGPB.81.4.12>
- Khan H, Gul R, Khan N U, Naz R, Shah S, Asim N & Latif A (2018). Role of selection indices in ascertaining high yielding drought stress tolerant chickpea (*Cicer arietinum* L.). *Journal of Animal & Plant Sciences* 28(2)
- Knight H & Knight M R (2001). Abiotic stress signaling pathways specificity and cross-talk. *Trends in Plant Science*, 6: 262–267
- Kotula L, Clode P L, De J, Cruz Jimenez L & Colmer T D (2019). Salinity tolerance in chickpea is associated with the ability to 'exclude' Na from leaf mesophyll cells. *Journal of Experimental Botany* 70(18): 4991–5002. <https://doi.org/10.1093/jxb/erz241>
- Kumar S, Li G, Yang J, Huang X, Ji Q, Liu Z, Ke W & Hou H (2021). Effect of Salt Stress on Growth, Physiological Parameters, and Ionic Concentration of Water Dropwort (*Oenanthe javanica*) Cultivars. *Frontiers in Plant Science*, 12. <https://doi.org/10.3389/FPLS.2021.660409>
- Kundu V, Sarkar M & Kundagrami S (2023). Screening of chickpea (*Cicer arietinum* L.) germplasms under salt stress. *Journal of Eco-Friendly Agriculture*. <https://doi.org/10.48165/jefa.2023.18.02.11>
- Kurunc A, Aslan G, Karaca C, Tezcan A, Turgut K, Karhan M, Kaplan B (2020). Stevia rebaudiana Bertoni'nin tuz kaynağı ve sulama suyu tuzluluğunun büyüme, verim ve kalite parametreleri üzerine etkileri. *Bilim Horticul*, 270, 109458.
- Laghmouchi Y, Belmehdi O, Bouyahya A, Skali Senhaji N & Abrini J (2017). Effect of temperature, salt stress and pH on seed germination of medicinal plant *Origanum compactum*. *Biocatalysis and Agricultural Biotechnology* 10: 156–160. <https://doi.org/10.1016/J.BCAB.2017.03.002>

- Lamba K, Kumar M, Singh V, Chaudhary L, Sharma R, Yashveer S & Dalal M S (2023). Heat stress tolerance indices for identification of the heat tolerant wheat genotypes. *Scientific Reports* 13(1): 10842
- Lavrenko S, Lavrenko N & Lykhovyd P V (2019). Effect of degree of salinity on seed germination and initial growth of chickpea (*Cicer arietinum*). *Biosystems Diversity* 27(2): 101–105. <https://doi.org/10.15421/011914>
- Li W, Zhang H, Zeng Y, Xiang L, Lei Z, Huang Q et al. (2020). A salt tolerance evaluation method for sunflower (*Helianthus annuus* L.) at the seed germination stage. *Scientific Reports* 10(1): 10626
- Liang W, Ma X, Wan P & Liu L (2018). Plant salt-tolerance mechanism: A review. *Biochemical and Biophysical Research Communications*, 495(1): 286–291. <https://doi.org/10.1016/J.BBRC.2017.11.043>
- Lin C S, Binns M R & Lefkovich L P (1986). Stability analysis: where do we stand? *Crop Science* 26: 894–900
- Ludwig M, Wilmes P & Schrader S (2018). Measuring soil sustainability via soil resilience. *Science of The Total Environment* 626: 1484–1493. <https://doi.org/10.1016/J.SCIOTENV.2017.10.043>
- Mann A et al. (2019). Physiological response of chickpea (*Cicer arietinum* L.) at early seedling stage under salt stress conditions. *Legume Research - An International Journal* 42(5).
- Meena H P, Kumar J & Ramesh M (2014). Evaluation of the reaction of chickpea (*Cicer arietinum* L.) genotypes to drought conditions using various stress tolerance indices. *Legume Research - An International Journal* 37(5): 453–459
- Mertens D (2005). AOAC official method 975.03. Metal in plants and pet foods. *Official Methods of Analysis*, 18th edn. Horwitz W & Latimer G W (Eds), pp. 3–4
- Moosavi S S, Samadi Y B, Naghavi M R, Zali A A, Dashti H & Pourshahbazi A (2008). Introduction of new indices to identify relative drought tolerance and resistance in wheat genotypes. *Desert* 12: 165–178
- Mukami A, Ng'etich A, Syombua E, Oduor R & Mbinda W (2020). Varietal differences in physiological and biochemical responses to salinity stress in six finger millet plants. *Physiology and Molecular Biology of Plants* 26(8): 1569–1582. <https://doi.org/10.1007/S12298-020-00853-8>
- Munns R & Tester M (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology* 59: 651–681. <https://doi.org/10.1146/ANNUREV.ARPLANT.59.032607.092911>
- Naseer M N, Rahman F U, Hussain Z, Khan I A, Aslam M M, Aslam A, Waheed H, Khan A U & Iqbal S (2022). Effect of Salinity Stress on Germination, Seedling Growth, Mineral Uptake and Chlorophyll Contents of Three Cucurbitaceae Species. *Brazilian Archives of Biology and Technology*, 65, e22210213. <https://doi.org/10.1590/1678-4324-2022210213>
- Navada S, Vadstein O, Gaumet F, Tveten A K, Spanu C, Mikkelsen Ø & Kolarevic J (2020). Biofilms remember: Osmotic stress priming as a microbial management strategy for improving salinity acclimation in nitrifying biofilms. *Water Research*, 176, 115732. <https://doi.org/10.1016/J.WATRES.2020.115732>
- Nayyar H (2003). Calcium as environmental sensors in plants. *Current Science India* 84: 7–10
- Okumuş O, Uzun S & Özaktan H (2023). Investigation of Some Forage Peas (*Pisum arvense* L.) in terms of Seed Yield under Kayseri Conditions. *International Journal of Agricultural and Natural Sciences* 3(16): 316–321
- Ozaktan H & Doymaz A (2022). Mineral composition and technological and morphological performance of beans as influenced by organic seaweed-extracted fertilizers applied in different growth stages. *Journal of Food Composition and Analysis* 114 pp
- Ozaktan H, Uzun S, Uzun O & Yasar Ciftci C (2023). Assessment of Agro-Morphological Traits of Common Bean Genotypes Grown Under Organic Farming Conditions with Multi-Variate Analyses and Applications. *Gesunde Pflanzen* 75(3): 515–523
- Özaktan H, Çiftçi C Y, Kaya M D, Uzun S, Uzun O & Akdoğan G (2018). Chloride salts inhibit emergence and seedling growth of chickpea rather than germination. *Legume Research*, 41(1): 60–66
- Özaktan H, Kibık G & Erol O (2022). Yeni Nohut (*Cicer arietinum* L.) Çeşitlerinin Kayseri Koşullarında Agro-morfolojik Özelliklerinin Belirlenmesi. *Erciyes Tarım ve Hayvan Bilimleri Dergisi* 5(2): 62–70
- Pan T, Liu M, Kreslavski V D, Zharmukhamedov S K, Nie C, Yu M, Kuznetsov V V, Allakhverdiev S I & Shabala S (2021). Non-stomatal limitation of photosynthesis by soil salinity. *Critical Reviews in Environmental Science and Technology* 51(8): 791–825. <https://doi.org/10.1080/10643389.2020.1735231>
- Pessarakli M & Szabolcs I (2016). Soil salinity and sodicity as particular plant/crop stress factors. *Handbook of Plant and Crop Stress*, Third Edition, 3–21. <https://doi.org/10.1201/9781351104609-1>
- Pessoa L G M, Freire M B G do S, Green C H M, Miranda M F A, Filho J C d A & Pessoa W R L S (2022). Assessment of soil salinity status under different land-use conditions in the semiarid region of Northeastern Brazil. *Ecological Indicators*, 141, 109139. <https://doi.org/10.1016/J.ECOLIND.2022.109139>
- Peterson A & Murphy K (2015). Ova kinoa çeşitlerinin sodyum klorür ve sodyum sülfat tuzluluğuna toleransı. *Mahsul Bilimi*, 55, 331–338.
- Pushpavalli R, Krishnamurthy L, Thudi M, Gaur P M, Rao M V, Siddique K H M, Colmer T D, Turner N C, Varshney R K & Vadez V (2015). Two key genomic regions harbour QTLs for salinity tolerance in ICCV 2 × JG 11 derived chickpea (*Cicer arietinum* L.) recombinant inbred lines. *BMC Plant Biology*, 15(1): 1–15. <https://doi.org/10.1186/S12870-015-0491-8>
- Reich M, Aghajanzadeh T, Parmar S, Hawkesford M J & De Kok L J (2018). Calcium ameliorates the toxicity of sulfate salinity in Brassica rapa. *Journal of Plant Physiology* 231: 1–8
- Rengasamy P (2010). Osmotic and ionic effects of various electrolytes on the growth of wheat. *Australian Journal of Soil Research* 48: 120–124
- Rosielle A A & Hamblin J (1981). Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Science* 21: 943–946
- Sandhu D, Cornacchione M V & Ferreira J F S (2017). Variable salinity responses of 12 alfalfa genotypes and comparative expression analyses of salt-response genes. *Scientific Reports*, 7, 42958. <https://doi.org/10.1038/srep42958>
- Sarita, Mehrotra S, Dimkpa C O & Goyal V (2023). Survival mechanisms of chickpea (*Cicer arietinum*) under saline conditions. *Plant Physiology and Biochemistry*, 205: 108168. <https://doi.org/10.1016/J.PLAPHY.2023.108168>
- Stavi I, Thevs N & Priori S (2021). Soil Salinity and Sodicity in Drylands: A Review of Causes, Effects, Monitoring, and Restoration Measures. *Frontiers in Environmental Science*, 9, 712831. <https://doi.org/10.3389/FENVS.2021.712831>
- Toderich K N, Mamadrahimov A A, Khaitov B B, Karimov A A, Soliev A A, Nanduri K R & Shuyskaya E V (2020). Differential impact of salinity stress on seeds minerals, storage proteins, fatty acids, and squalene composition of new Quinoa genotype, grown in hyper-arid desert environments. *Frontiers in Plant Science*, 11, 607102. <https://doi.org/10.3389/fpls.2020.607102>
- Toklu F, Gupta D, Sen, Karaköy T & Özkan H (2021). Bioactives and Nutraceuticals in Food Legumes: Nutritional Perspective. In *Breeding for Enhanced Nutrition and Bio-Active Compounds in Food Legumes* (pp. 229–245). https://doi.org/10.1007/978-3-030-59215-8_10

- Tounsi S, Feki K, Hmidi D, Masmoudi K & Brini F (2017). Salt stress reveals differential physiological, biochemical and molecular responses in *T. monococcum* and *T. durum* wheat genotypes. *Physiology and Molecular Biology of Plants* 23(3): 517–528. <https://doi.org/10.1007/s12298-017-0457-4>
- Voisin T, Erriguible A & Aymonier C (2019). Influence of multiphasic systems on salt(s) solubility in supercritical water: the case of NaCl and NaCl-Na₂SO₄. *The Journal of Supercritical Fluids* 152, 104567
- Wang J, Zhao Y G, Pang H C, Zhang L & Li Y Y (2016). Grain shape as a predictor of salt tolerance in sunflower. *Agronomy Journal* 108: 2280–2288
- Yuan Y (2011). Multiple imputation using SAS software. *Journal of Statistical Software*, 45, 1–25.
- Zeeshan M, Lu M, Sehar S, Holford P & Wu F (2020). Comparison of biochemical, anatomical, morphological, and physiological responses to salinity stress in wheat and barley genotypes differing in salinity tolerance. *Agronomy* 10(1): 127. <https://doi.org/10.3390/agronomy10010127>
- Zehra A, Gul B, Ansari R & Khan M A (2012). Role of calcium in alleviating effect of salinity on germination of *Phragmites karka* seeds. *South African Journal of Botany*, 78, 122–128.
- Zhang Q & Dai W (2019). Plant Response to Salinity Stress. In *Stress Physiology of Woody Plants* (pp. 155–173). <https://doi.org/10.1201/9780429190476-7>
- Zörc C, Geilfus C M & Dietz K J (2019). Salinity and crop yield. *Plant Biology* 21: 31–38. <https://doi.org/10.1111/PLB.12884>



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