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Responses of Some Bread Wheat (*Triticum aestivum* L.) Cultivars to Salinity Stress During Germination and Early Seedling Development Stages

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ABSTRACT

This study aimed to assess the NaCl tolerance of 10 bread wheat (*Triticum aestivum* L.) cultivars during germination and early seedling development. The evaluation was conducted on shoot dry weight and shoot length across five salt concentrations (0, 4, 8, 12, and 16 dS m^{-1}).The effects of salt treatment, variety, and the interaction between salt and variety were statistically significant (P<0.01, P<0.05) for all examined wheat varieties (Serince, Hamza, NKÜ Lider, Almeria, Adana99, Bora, Eksperia, Falado, Selimiye, Gelibolu). Regression analysis and GGE biplot analysis were conducted to assess varieties under various salt treatments, treating the salt treatments as "environments." The GGE biplot accounted for 97% of the overall variation. The relative positions of variety in the regression graphs and GGE biplot graphs were congruent. The varieties NKÜ Lider, Serince, Bora, and Almeria had a lesser reduce in weight under salt stress compared to the control and demonstrated positive PC1 and PC2 values, thus being recognized as the most salt-tolerant. Conversely, the cultivars Adana99, Selimiye, and Gelibolu, which exhibited low shoot dry weight under control conditions and were significantly impacted by salt treatments, were identified as the most salt-sensitive. The GGE biplot approach determined 8 dS m^{-1} as the threshold for salt tolerance based on the average axis utilized for variety selection. The paper indicates that integrating regression analysis with GGE biplot analysis in future investigations of salt-tolerant genotypes will enhance selection efficacy for researchers.

Key words: Bread wheat, Salinity stress, Germination, Seedling Development

Bazı Ekmeklik Buğday (*Triticum aestivum* L.) Çeşitlerinin Çimlenme ve Erken Fide Gelişim Aşamalarında Tuzluluk Stresine Tepkileri

ÖZ

Bu çalışma 5 adeti 2014 ve öncesi, 5 adeti ise 2014 yılından sonra tescil edilen 10 adet ekmeklik buğday (*Triticum aestivum L.)* çeşidinin çimlenme ve erken fide döneminde 5 tuz konsantrasyonunda (0, 4, 8, 12,16 dS m^{-1}) tuzluluğa toleranslarını sürgün kuru ağırlığı ve sürgün uzunluğu üzerinden değerlendirmek amacıyla yürütülmüştür. Araştırılan bütün ekmeklik buğday çeşitlerinde (Serince, Hamza, NKÜ Lider, Almeria, Adana99, Bora, Eksperia, Falado, Selimiye, Gelibolu) tuz uygulaması, çeşit, tuz x çeşit interaksiyonu istatiksel olarak önemli olmuştur (P<0.01, P<0.05). Farklı tuz uygulamalarında çeşitleri değerlendirmek amacıyla regresyon analizi ve GGE biplot analizi (tuz uygulamaları = çevre) yapılmıştır. GGE biplot analizi toplam varyasyonun %97'sini açıklamıştır. Her çeşide ait oluşturulan regresyon grafikleri ile GGE biplot grafiklerinde çeşitlerin konumları birbirleri ile uyumlu olmuştur. Kontrol uygulamasında yüksek ağırlığa sahip olan tuz uygulamalarına göre ağırlığı daha az değişen NKÜ Lider, Serince, Bora ve Almeria çeşitleri pozitif PC1 ve PC2 değerleri ile tuzluluğa en dayanıklı çeşitler olarak belirlenmiştir. Kontrol uygulamasında yüksek kuru sürgün ağırlığı ve sürgün uzunluğuna sahip olan ancak, tuz uygulamaları ile ağırlık azalma oranı en fazla olan Adana99, Gelibolu ve Selimiye çeşitlere ait PC2 değerleri de düşük gerçekleşmiştir. Kontrol uygulamasında düşük ağırlığa salip olan ve tuz uygulamalarında yüksek oranda olumsuz olarak etkilenen Adana99, Selimiye ve Gelibolu çeşitleri tuzluluğa en hassas çeşitler olarak belirlenmiştir. GGE biplot yönteminde çeşit seleksiyonu için kullanılan ortalama eksene göre tuzluluk eşik değeri 8 dS m^{-1} olarak belirlenmiştir. Tuzluluğa dayanıklı genotipleri belirlemek amacıyla yürütülecek araştırmalarda, regresyon analizi ile GGE biplot analizinin birlikte kullanılması araştırıcıları daha başarılı seleksiyon yapmasını sağlayacaktır.

Anahtar Kelimeler: Ekmeklik buğday, Tuzluluk stresi, Çimlenme, Fide Gelişimi

INTRODUCTION

The swift escalation of the global population and climate change resulting from unsustainable human practices have exerted considerable strain on agricultural output. The agricultural industry is acutely affected by climatic changes, especially abiotic stressors like salt, which adversely influence crop output. FAO statistics indicate that the global population is projected to attain 9.3 billion by 2050, requiring a 35% to 56% rise in food demand. Climate change is anticipated to increase overall food demand by as much as 62%, increasing worries over global food security (Van Dijk et al., 2021). The prevalence of undernourishment is increasing, with almost 768 million individuals (9.9% of the global population) currently experiencing hunger (Marson et al., 2023).

Natural water sources generally contain dissolved minerals and ions, with concentrations varying based on ambient circumstances. Climate change and global warming are modifying the hydrological cycle, impacting both the volume and physicochemical characteristics of water resources. Global warming elevates atmospheric evaporation rates, diminishing total water supplies and augmenting the mineral concentration of the remaining water.

Drought, along with heightened evaporation, intensifies salt deposition on the soil surface, resulting in osmotic stress in plant cells. Salinity stress adversely impacts photosynthetic rates, cellular metabolism, and overall plant growth, leading to diminished agricultural yields.

Abiotic environmental pressures are a primary factor in the reduction of yield in global agricultural output. Studies demonstrate that these stressors diminish the average yield of numerous basic crops by over 50% globally (Koyro et al., 2008). Drought is regarded as the primary stressor, posing a substantial danger to agricultural output (Liang, 2016). Salinity, the second most significant environmental stressor, severely limits agricultural performance and productivity (Wang et al., 2003; Li et al., 2020). Salinity stress adversely impacts agricultural ecosystems, resulting in diminished productivity and decreased biodiversity (Ashraf & Foolad, 2007). The negative impact of salinity on plants is exacerbated in dry and semi-arid settings. Environmental stressors are most pronounced during germination, seedling development, and early growth phases (Demir et al., 2003). Kanber and Ünlü (2010) reported that high salt concentrations significantly inhibit water absorption in the root zone, while deterioration of the soil structure worsens water uptake by plants and prevents water transport to the roots.

About one-third of agricultural land is affected by salt issues, with estimates varying from 400 to 950 million hectares (Hasegawa et al., 1986; Özkaldı et al., 2004; Taghipour & Salehi, 2008). Each year, approximately 10 million hectares of agricultural land are rendered unproductive because of salt accumulation. In Türkiye, approximately 1.5 million hectares of agricultural land are affected by salinity (TÜİK, 2004). Salinity's impact on plant development differs between species. Cereals, especially during germination and early seedling phases, exhibit significant sensitivity to increased salinity (Ghoulam & Fares, 2001). With increasing salinity stress, germination rates diminish, plant height drops, and both leaf area and tiller numbers are reduced (Gupta & Srivastava, 1989; Pessarakli et al., 1991). Begum et al. (1992) indicated that NaCl stress diminishes germination rates in wheat, but Vardar et al. (2014) noted considerable reductions in root length, shoot height, and germination vigor with escalating salt concentrations. Benlioğlu et al. (2015) also recorded detrimental alterations in the growth and development metrics of plants subjected to salt stress.

Wheat is the most extensively cultivated and consumed cereal worldwide, including in Turkey. Data from 2021-2022 indicates that per capita wheat consumption in Turkey rose by 7.4% to 179.5 kg, while food-grade wheat utilization increased by 8.9% to 15.18 million tons (TÜİK, 2022). Ensuring the sustainability of wheat production necessitates the creation of cultivars resistant to biotic and abiotic challenges, alongside the application of suitable farming techniques. Plants react to stress circumstances via resistance, tolerance, and adaptability mechanisms (Mooney & Hobbs, 1986; Pagán & García-Arenal, 2018). To attain agricultural sustainability, it is imperative to develop cultivars that maintain soil health, optimize water resource usage, and endure climatic change. Bread wheat (*Triticum aestivum* L.) is a crucial crop extensively grown in different countries and functions as a primary food source globally (Shewry, 2009). Nonetheless, wheat productivity is negatively impacted by numerous abiotic stressors. Salinity stress specifically impairs physiological and biochemical processes, hence restricting growth and development (Wang et al., 2003). Studies indicate that wheat yields diminish by roughly 7% when salt concentrations surpass 6 dS/m (Shannon, 1998). Extended exposure to salinity inflicts irreparable harm on plant physiology, rendering yield loss unavoidable (Munns & Tester 2008).

Consequently, thorough investigations into the salt tolerance mechanisms of wheat cultivars will facilitate the creation of high-yield, salt-resistant variants via modern breeding methodologies. This research enhances sustainable wheat production and is crucial for bolstering global food security. Regression analysis is employed to ascertain the salt tolerance levels of genotypes in several plant species (Kandil et al., 2012; Güldüren & Elkoca, 2012; Nasüaku et al., 2013; Lavrenko et al., 2019). GGE biplot analysis is a graphical technique for elucidating trial outcomes across diverse habitats, assisting researchers in determining the optimal genotypes for particular situations and identifying the most suitable environments for selection (Akçura et al., 2019).

In the research, the effects of five different Electrical Conductivity (ECi) levels [Control (0), 4, 8, 12 and 16 dS m^{-1}] prepared with NaCl salt on shoot dry weights and lengths of 10 bread wheat varieties were investigated. Stress tolerance index (STI) values were used to evaluate the variety tolerance levels using regression analysis and GGE biplot methodologies.

MATERIALS AND METHODS

This experiment aimed to assess the impact of salinity stress, induced by varying NaCl concentrations, on the germination and initial seedling growth of bread wheat cultivars commonly cultivated in Turkey, namely in the Çanakkale, Marmara, and Thrace regions. Bread wheat varieties used in the research and the organizations they are registered with are shown in Table 1.

Table 1. Information of the cultivars used in the study

No	Cultivar Name	Registering Institution	Registration Year
1	Serince	GAP Agricultural Research Institute	2021
2	Hamza	Tekcan Seed Company	2015
3	NKÜ Lider	NKÜ Faculty of Agriculture	2016
4	Almeria	Alfa Seed Company	2019
5	Adana99	Eastern Mediterranean Agricultural Research Institute	1999
6	Bora	Tasaco Agriculture	2014
7	Falado	Syngenta Agriculture	2021
8	Esperia	Tasaco Agriculture	2011
9	Selimiye	Trakya Agricultural Research Institute	2009
10	Gelibolu	Trakya Agricultural Research Institute	2005

The experiment was carried out in the 2024-2025 growing season at the İçdaş Agriculture, Seed, and Technology Laboratory. The research utilized a split-plot design with three replications, wherein cultivars constituted the main plots and five NaCl solutions (0, 4, 8, 12, and 16 dS m^{-1}) served as the sub-plots. Sterilized distilled water was utilized to formulate salt solutions to mitigate the influence of extraneous chemical variables. Seeds were surface sterilized using a 2% sodium hypochlorite solution, then rinsed three times with sterilized distilled water. Sterilized seeds were positioned in 9 cm diameter petri dishes containing 10 ml of saline solution, with 20 seeds per dish, interleaved between sterilized germination papers. To inhibit evaporation, petri plates were encased in cling film and positioned within sealed transparent plastic bags. The dishes were subsequently positioned in a climate-controlled laboratory with a 16-hour light and 8-hour dark cycle at 25 ±1°C for 8 days for germination (ISTA, 1996) and 14 days for initial seedling development. Seeds were considered germinated when radicles attained a length of 2 mm (Adjel et al., 2013). Germination papers and saline solutions were substituted bi-daily throughout the experiment.

Shoot dry weight and shoot length were employed to assess cultivar tolerance levels. The maximum dosage (16 dS m^{-1}) was omitted from assessment due to inadequate data. STI values were computed for each concentration according to the methodology outlined by Rasheed et al. (2015). Data were examined by individual variance analyses for each concentration, a combined variance analysis for cultivar × salt concentration interactions, regression analysis, and GGE biplot analysis.

Biplot analysis relies on the graphical depiction of matrices derived from principal component analysis (Gabriel, 1971), with axes designated as PC1 and PC2.This study utilized GGE biplot analysis to determine that cultivars with PC1 > 0.0 exhibited greater shoot dry weights and lengths in saline conditions, whereas PC1 < 0.0 signified sensitivity to salinity. PC2 values approaching 0.0 showed stability under saline treatments, while elevated PC2 values signified instability. Vector lengths and placements of salt concentrations in relation to the average salt concentration were utilized for cultivar selection and the establishment of crucial salt tolerance thresholds. Variance analyses were executed utilizing SAS JMP (SAS Institute, 2004), and biplot analyses were carried out employing GGE-biplot (Yan, 2014).

RESULTS AND DISCUSSION

The shoot dry weights and lengths of the cultivars were strongly influenced by the salt levels applied. An increase in salt content (from 0 dS m^{-1} to 12 dS m^{-1}) resulted in a significant decrease in shoot dry weights and lengths.

The shoot dry weight mean of the control group was measured 12.27 g. The cultivars with the highest shoot dry weights were Bora (11.93 g), NKÜ Lider (10.90 g), and Falado (10.77 g). The lowest shoot dry weight was recorded in Adana99 (6.43 g), succeeded by Selimiye (6.87 g), Gelibolu (7.77 g), and Esperia (8.37 g).

In terms of shoot lengths, the control group exhibited the greatest value from the Hamza cultivar, measuring 19.65 cm. The subsequent records were Serince (17.32 cm), Bora (17.21 cm), and Falado (16.02 cm), with Almeria recording the lowest result at 13.50 cm.

At a salt concentration of 4 dS m^{-1}, the mean shoot dry weight was 8.90 g. The greatest weight in this therapy was recorded for Bora (11.87 g), followed by Serince (11.32 g). Adana99 exhibited the lowest weight, followed by Selimiye and Gelibolu (6.89–6.56 g).

Regarding shoot lengths at this concentration, the average length was 14.43 cm, with Serince, Hamza, and NKÜ Lider showing the highest values (16.01–16.05–15.53 cm). The remaining seven cultivars fell below the average, with Esperia exhibiting the shortest shoot length at 13.12 cm.

At 8 dS m^{-1}, the mean shoot dry weight was 7.26 g.The maximum value was recorded from Bora, succeeded by Falado (8.68 g) and Serince (8.60 g). Conversely, Adana99 demonstrated the lowest shoot dry weight at 3.60 g, significantly lower than all other entries. The mean shoot length at this salinity was 11.95 cm, with Hamza exhibiting the maximum value of 13.38 cm and Gelibolu the minimum at 10.70 cm.

At 12 dS m^{-1}, the highest shoot dry weight was recorded in Falado (4.32 g), succeeded by Serince (4.12 g) and Bora (4.01 g). The minimum value was documented for Selimiye (2.66 g). The mean shoot length at this salinity was 4.32 cm, with NKÜ Lider exhibiting the greatest measurement, succeeded by Falado at 4.92 cm and Bora at 4.91 cm.

The Stress Tolerance Index (STI) is a frequently utilized measure for identifying stress-tolerant cultivars. STI measures reductions in shoot dry weight and shoot length under stress conditions relative to the control group, with cultivars exhibiting higher STI values being tolerant (Akçura et al., 2011; Rasheed et al., 2015).

A notable decline was noted in all varieties when salinity rose from 4 dS m^{-1} to 12 dS m^{-1}. In terms of shoot dry weight data, at a saline level of 4 dS m^{-1}, the cultivars NKÜ Lider, Bora, and Selimiye demonstrated superior values relative to the control group (1.047–1.041–1.042). The Gelibolu cultivar had the lowest shoot dry weight value (0.608 g) within the same salinity group. At salt levels below 8 dS m^{-1}, the greatest STI value was recorded for Selimiye (0.958), followed by Esperia (0.885) and Almeria (0.861). The minimum values were documented in Adana99 (0.537) and Gelibolu (0.552). At 12 dS m^{-1} salinity, the highest value was observed in Adana99 (0.429), while the lowest was in Gelibolu (0.265). The mean STI value for all kinds was 0.929 at 4 dS m^{-1}, declining to 0.767 and 0.366 at elevated salinity levels of 8 and 12 dS m^{-1}, respectively. In comparison to the 4 dS m^{-1} treatment, STI levels decreased by 17.4% at 8 dS m^{-1} and by 60.6% at 12 dS m^{-1}. The analysis of the table indicated that, in comparison to the control group, the Adana99 variety exhibited the most significant reduction (38%) under 4 dS m^{-1} salinity. At a salinity of 8 dS m^{-1}, the Esperia variety demonstrated the most substantial loss (59%), but at 12 dS m^{-1} salinity, the Bora variety exhibited the largest reduction (67%).

Table 2. Stress tolerance indices of shoot dry weight and shoot length of cultivars according to applied salinity

Cultivars	Shoot Length (cm)				Shoot Dry Weight (mg)				Shoot Length (cm)			Shoot Dry Weight (mg)		
	Salt Concentrations(dS m^{-1})				Salt Concentrations(dS m^{-1})				Stress Tolerance Index			Stress Tolerance Index		
	0	4	8	12	0	4	8	12	4	8	12	4	8	12
Serince	17.32	16.01	12.69	4.35	12.27	10.5	8.6	4.07	0.936	0.742	0.254	0.929	0.761	0.36
Hamza	19.65	16.05	13.38	2.82	9.9	9.65	8.32	3.85	0.825	0.688	0.145	0.924	0.79	0.368
NKÜ Lider	15.36	15.53	13.35	6.08	10.9	11.1	8.2	3.98	1.037	0.891	0.406	1.047	0.774	0.374
Almeria	13.5	13.81	10.72	4.12	8.7	8.12	7.23	2.98	1.013	0.781	0.309	0.968	0.861	0.354
Adana99	14.93	13.76	11.57	3.55	6.43	5.78	3.6	2.85	0.933	0.784	0.241	0.861	0.537	0.429
Bora	17.21	14.83	12.49	4.91	11.93	11.87	8.85	4.01	0.822	0.692	0.272	1.041	0.781	0.348
Falado	16.02	14.85	12.07	4.92	10.77	10.1	8.68	4.32	0.887	0.721	0.294	0.902	0.774	0.387
Esperia	14.01	13.12	11.57	4.06	8.37	7.56	6.87	2.78	0.941	0.83	0.291	0.97	0.885	0.359
Selimiye	13.67	13.21	10.96	4.44	6.87	6.56	6.02	2.66	0.963	0.799	0.324	1.042	0.958	0.418
Gelibolu	14.5	13.13	10.7	3.92	7.77	6.89	6.24	3.01	0.768	0.626	0.229	0.608	0.552	0.265
Avg.	15.62	14.43	11.95	2.82	9.39	8.81	7.26	3.45						
Min.	13.5	13.12	10.7	3.92	6.43	5.78	3.6	2.66						
Max.	19.65	16.05	13.38	6.08	12.27	11.87	8.85	4.32						
Genotype	**	*	**	**	**	**	**	*						
CV	6.19	7.54	9.53	18,24	5.84	8.64	10.91	15.99						
R2	0.85	0.8	0.65	0.61	0.85	0.8	0.65	0.54						

**: P< 0.01, LSD: Least Significant Difference, CV: Coefficient of Variation, R2: Coefficient of Regression

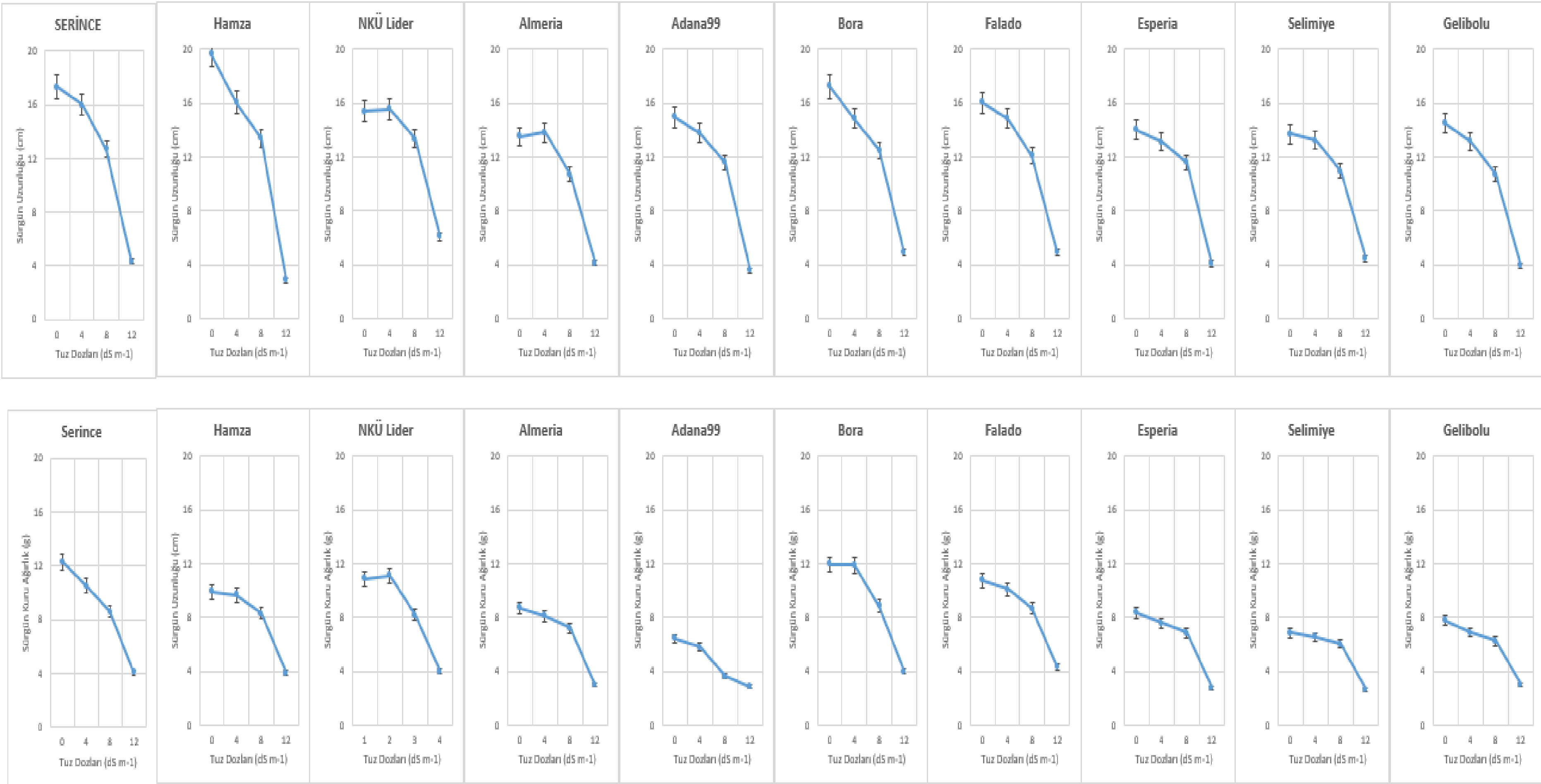

Figure 1. Variations in shoot dry weight and shoot length according to the salt concentrations applied to the varieties

In terms of shoot length, the NKÜ Lider variety exhibited the highest STI value under the 4 dS m^{-1} salt treatment compared to the control group, whereas the Gelibolu variety recorded the lowest value (0.768). In the 8 dS m^{-1} treatment, NKÜ Lider exhibited the highest result at 0.891, followed by Esperia at 0.830. The Gelibolu variety again recorded the lowest rating at 0.626. In the 12 dS m^{-1} salt treatment, NKÜ Lider exhibited the highest value at 0.406, whilst the Hamza variety recorded the lowest value at 0.145.

The 4 dS m^{-1} salt treatment resulted in an average shoot length STI value of 0.913 across all types. For other salt treatments, the results were 0.756 and 0.277, respectively. The 4 dS m^{-1} salt treatment resulted in a 0.913 value, while the 8 dS m^{-1} treatment decreased it by 17.2%. This value decreased by 70% after the 12 dS m^{-1} treatment.

The Almeria variety experienced the biggest percentage loss (23% compared to the control group) under the 4 dS m^{-1} salt treatment. The Hamza variety showed the largest decline (79%) under the 8 dS m^{-1} treatment. Similarly, the 12 dS m^{-1} salt treatment resulted in a 67% decrease.

As with all of these findings, similar experiments undertaken by various researchers have revealed that differences in germination rates are critical in determining salinity tolerance (Saxena et al., 1994). For these reasons, seed germination in petri dishes under saline conditions is commonly employed to quickly assess salt tolerance (Jana and Slinkard, 1976). Many researchers have used petri dishes containing different salt solutions to test salt tolerance in various plant species (beans, sorghum, bread wheat, vegetables) (Goertz and Coons, 1989; Elkoca, 1997; Esechie, 1994; Kırtok et al., 1994; Cucci et al., 1994), and resistant species and varieties were identified in a short time.

The adaptability of plants to specific adverse situations differs based on their growth phases; nonetheless, possessing a robust seedling structure is crucial (Akram et al., 2010). Expeditious and uniform seed germination throughout germination phases, together with swift development in the initial seedling stages, are crucial for plant cultivation in salty soils (Foolad, 2004; Ashraf et al., 2008). In the cultivation of bread wheat, the germination and initial seedling development stages are identified as the periods during which plants exhibit heightened sensitivity to unfavorable environments (Ashraf and Lin, 1994). The GGE biplot approach is one of the most effective techniques for visually assessing the responses of cultivars to varying environments. Consequently, GGE biplot analysis was employed to visually assess the tolerance levels of bread wheat cultivars subjected to various salt treatments. The variety exhibiting the greatest shoot weight and shoot length at specific salt concentrations was identified, as well as the variety demonstrating optimal tolerance to particular salt treatments (Akçura, 2021).

The biplot illustrated in Figures 2-3 is utilized to ascertain which variety had the greatest dry shoot weight and shoot length at specific salt concentrations, as well as to identify which variety demonstrated superior tolerance at those concentrations.

Analysis of PC1 axis values indicated a positive correlation between varietal salt tolerance levels and ascending PC1 scores, with the NKÜ Lider, Bora, Selimiye, and Esperia varieties exhibiting the highest shoot dry weights/lengths and maximum PC1 values, whereas varieties with PC2 values near 0.0 displayed enhanced relative tolerance. The GGE biplot enabled visual analysis of inter concentration interactions, with vector angle cosine values (Yan, 2014) statistically illustrating correlations with salt doses, demonstrating a gradual angular expansion from control to 12 dS m^{-1} (minimum angle: 4-8 dS m^{-1}; maximal angle: 12 dS m^{-1}). Biplot analysis of treatment responses (Figures 2-3) revealed that NKÜ Lider, Bora, and Selimiye consistently surpassed mean shoot dry weight values with positive PC1 positioning, while NKÜ Lider, Almeria, Serince, and Esperia excelled in shoot length parameters, all clustering within the biplot's tolerant zone. The graphical analyses (Figures 2-3) elucidated concentration-specific selection efficacy, with the 12 dS m^{-1} treatment demonstrating the highest discriminative power for tolerance screening.

It was noted that an increase in the saline tolerance index (STI) corresponded with a decrease in the dry weights and lengths of the cultivars. Bread wheat varieties demonstrated comparable alterations in shoot dry weight and shoot length under both control and 4 dS m^{-1} conditions. The varieties NKÜ Lider, Almeria, and Bora produced results that were comparable to the control group for both measures. Moreover, at 8 and 12 dS m^{-1} levels, the decreases in dry shoot weight and shoot length were more significant, with the salt-treated groups exhibiting notable reductions relative to the control. The 8 dS m^{-1} salinity level was identified as the most effective electrical conductivity (ECi) level, as demonstrated by data from prior and subsequent salinity levels. This indicates that 8 dS m^{-1} is theoretically near the optimal selection threshold and may improve selection efficiency if utilized as a critical parameter in breeding efforts for bread wheat.

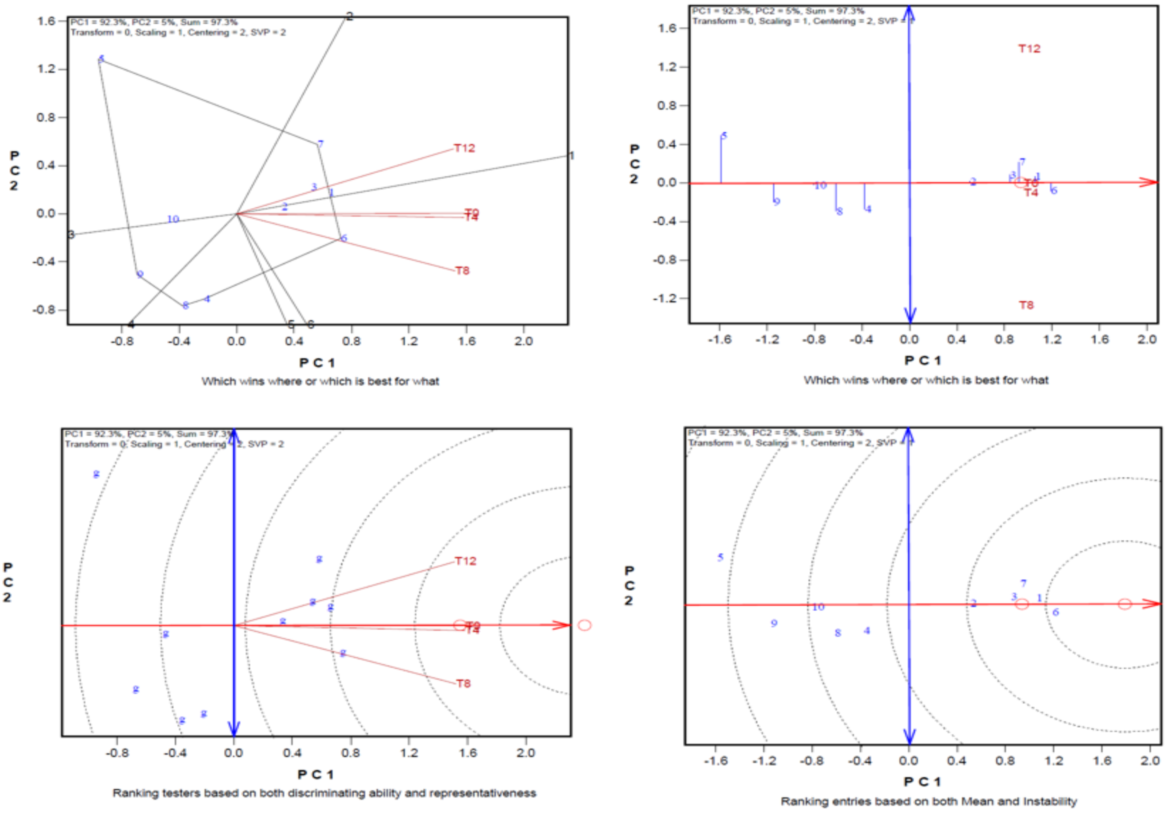

Figure 2. Interaction of genotype and salt concentration on shoot dry weight illustrated by GGE biplot graphics.

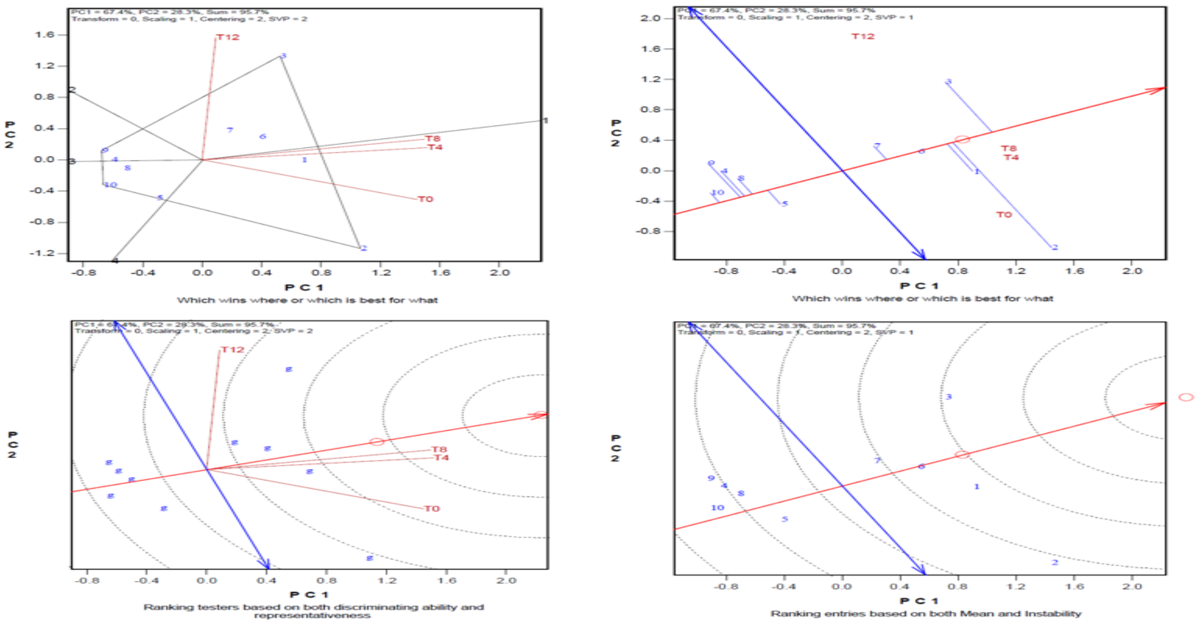

Figure 3. GGE biplot graphics illustrating the interaction between genotype and salt concentration on shoot length

This work utilized the GGE biplot approach, created by plant breeders for analyzing genotype × environment (G×E) interactions in multi-environment yield trials (Yan, 2014), alongside regression analysis, commonly applied to evaluate stress tolerance. Regression graphs and GGE biplots enabled the depiction of varietal responses to various salt treatments (Akçura, 2021).

The regression analysis indicated that varieties with the most significant disparities in maximum and minimum shoot dry weight and shoot length under saline stress conditions (NKÜ Lider, Bora, Serince) displayed low PC2 values in the biplot analysis. The GGE biplot methodology, treating salt concentrations as separate environments, successfully delineated: (1) the superior varieties at specific salinity levels, (2) the most tolerant varieties across all concentrations, (3) the ideal salt concentrations for genotype selection, (4) the interrelationships among varying salt concentrations, and (5) the most salt-sensitive varieties. The analytical methods effectively achieved the main research goal of identifying salt-tolerant cultivars, as the GGE biplot analysis allowed for an in-depth assessment of genotype performance under different salinity levels, offering critical insights for breeding programs focused on creating stress-resistant wheat varieties.

In the GGE biplot analysis, all salt concentrations demonstrated positive PC1 values, however the control and 4 dS m^{-1} treatments revealed negative PC2 values, with the remaining salt treatments exhibiting positive PC2 values. Significantly, at salinity levels of 8 dS m^{-1} and above (except 16 dS m^{-1}, where germination occurred without following shoot and root development in all bread wheat varieties), there were large reductions in shoot dry weight and length, which correlated with substantial fluctuations in PC2 values. A comparative examination indicated little changes in PC1 values among salt concentrations, but PC2 values exhibited significant variance. The data indicate that for salinity-based varietal selection, the PC2 axis is a more effective criterion than the PC1 axis, offering superior discriminative power for selecting salt-tolerant genotypes under diverse stress circumstances.

CONCLUSION

In conclusion, the combined GGE biplot and regression studies definitively indicated NKÜ Lider, Serince, Bora, and Almeria as the most salt-tolerant cultivars, whereas pre-2014 types (Selimiye, Adana99, Gelibolu) shown significant salt sensitivity. The research determined that utilizing 8 dS m^{-1} ECi as a selection criterion effectively selects genotypes exhibiting both extensive adaptability and salt tolerance in bread wheat breeding. Moreover, the integration of regression analysis and GGE biplot approach with traditional variance analysis markedly improves the selection efficiency for genotypes tolerant to abiotic stress, especially in saline environments. This comprehensive analytical method equips breeders with effective tools for enhanced genotype selection in stress breeding initiatives.

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Author Contributions

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REFERENCES

Adjel, F., Bouzerzour, H., & Benmahammed, A. (2013). Salt stress effects on seed germination and seedling growth of barley (Hordeum vulgare L.) genotypes. *Journal of Agriculture and Sustainability, 3*(2), 1–9.

Akçura, S. (2021). Sebze tipi sakız fasulyesinde tuza toleranslı genotiplerin araştırılması. *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi, 24*(1), 99–107.

Akçura, M., Partigoç, F., & Kaya, Y. (2011). Evaluating drought stress tolerance based on selection indices in Turkish bread wheat landraces. *Journal of Animal and Plant Sciences, 21*(4), 700–709.

Akçura, M., Turan, V., Kokten, K., & Kaplan, M. (2019). Fatty acid and some micro element compositions of cluster bean (Cyamopsis tetragonoloba) genotype seeds growing under Mediterranean climate. *Industrial Crops and Products, 128*, 140–146. https://doi.org/10.1016/j.indcrop.2018.11.036

Akram, M., Ashraf, M. Y., Ahmad, R., Waraich, E. A., Iqbal, J., & Mohsan, M. (2010). Screening for salt tolerance in maize (Zea mays L.) hybrids at an early seedling stage. *Pakistan Journal of Botany, 42*(1), 141–154.

Ashraf, M., Athar, H. R., Harris, P. J. C., & Kwon, T. R. (2008). Some prospective strategies for improving crop salt tolerance. *Advances in Agronomy, 97*, 45–110. https://doi.org/10.1016/S0065-2113(07)00002-8

Ashraf, M., & Lin, W. (1994). Breeding for salinity tolerance in plants. *Critical Reviews in Plant Sciences, 13*(1), 17–42. https://doi.org/10.1080/07352689409701906

Ashraf, M., & Foolad, M. R. (2007). Improving plant abiotic-stress resistance by exogenous application of osmoprotectants glycine betaine and proline. *Environmental and Experimental Botany, 59*(2), 206–216. https://doi.org/10.1016/j.envexpbot.2005.12.006

Baldwin, A. H., McKee, K. L., & Mendelssohn, I. A. (1996). The influence of vegetation, salinity, and inundation on seed banks of oligohaline coastal marshes. *American Journal of Botany, 83*(4), 470–479. https://doi.org/10.2307/2446200

Begum, F., Karmoker, J. L., Fattah, Q. A., & Maniruzzaman, A. F. M. (1992). Effect of salinity and its correlation with K+, Na+, and Cl– accumulation in germinating seeds of *Triticum aestivum* L. cv. Akbar. *Plant and Cell Physiology, 33*(7), 1009–1014.

Benlioğlu, B., & Özkan, U. (2015). Farklı arpa çeşitlerinin çimlenme dönemlerinde tuz stresine tepkileri. *Tarla Bitkileri Merkez Araştırma Enstitüsü Dergisi, 24*(2), 109–114.

Cucci, G., De Caro, A., Ciciretti, L., & Leoni, B. (1994). Salinity and seed germination of some vegetable crops. In *Proceedings of International Symposium on Agrotechnics and Storage of Vegetable and Ornamental Seeds* (pp. 305–310).

Demir, I., Mavi, K., & Okçu, G. (2003). Effect of salt stress on germination and seedling growth in serially harvested aubergine (Solanum melongena L.) seeds during development. *Israel Journal of Plant Sciences, 51*, 125–131. https://doi.org/10.1560/NF40-VY7R-2T8B-CEAJ

Elkoca, E. (1997). Fasulye (Phaseolus vulgaris L.)'de tuza dayanıklılık üzerine bir çalışma [Unpublished master's thesis]. Atatürk Üniversitesi, Erzurum, Türkiye.

Esechie, H. A. (1994). Interaction of salinity and temperature on the germination of sorghum. *Journal of Agronomy and Crop Science, 172*(3), 194–199. https://doi.org/10.1111/j.1439-037X.1994.tb00169.x

Foolad, M. R. (2004). Recent advances in genetics of salt tolerance in tomato. *Plant Cell, Tissue and Organ Culture, 76*(2), 101–119. https://doi.org/10.1023/B:TICU.0000007308.47649.57

Gabriel, K. R. (1971). The biplot graphic display of matrices with application to principal component analysis. *Biometrika, 58*(3), 453–467. https://doi.org/10.1093/biomet/58.3.453

Ghoulam, C., & Fares, K. (2001). Effect of salinity on seed germination and early seedling growth of sugar beet (Beta vulgaris L.). *Seed Science and Technology, 29*, 357–364.

Goertz, S. H., & Coons, J. M. (1989). Germination response of tepary and navy beans to sodium chloride and temperature. *HortScience, 24*(6), 923–925.

Gupta, J. K., Srivastava, A. B., & Sharma, K. K. (1989). Estimation of true change using additional information provided by an auxiliary variable. *Journal of Experimental Education, 57*(2), 143–150.

Güldüren, Ş., & Elkoca, E. (2012). Fasulye genotiplerinin tuza toleransları. *Atatürk Üniversitesi Ziraat Fakültesi Dergisi, 43*(1), 29–41.

Hasegawa, P. M., Bressan, R. A., & Handa, A. K. (1986). Cellular mechanisms of salinity tolerance. *HortScience, 21*(6), 1317–1324.

He, M., He, C. Q., & Ding, N. Z. (2018). Abiotic stresses: General defenses of land plants and chances for engineering multistress tolerance. *Frontiers in Plant Science, 9*, 1771. https://doi.org/10.3389/fpls.2018.01771

Jana, M. K., & Slinkard, A. E. (1976). Screening for salt tolerance in lentil. *Lens Newsletter, 6*, 5–27.

Kanber, R., & Ünlü, M. (2010). *Tarımda su ve toprak tuzluluğu*. Ç.Ü. Ziraat Fakültesi Yayınları.

Kandil, A. A., Sharief, A. E., & Ahmed, S. R. H. (2012). Germination and seedling growth of some chickpea cultivars (Cicer arietinum L.) under salinity stress. *Journal of Basic and Applied Sciences, 8*(2), 561–571.

Kırtok, Y., Veli, S., Tükel, T., Düzenli, S., & Kılınç, M. (1994). Evaluation of salinity stress on germination characteristics and seedling growth of 3 bread wheats. In *Proceedings of Tarla Bitkileri Kongresi* (Vol. 1, pp. 57–61). E.Ü. Ziraat Fakültesi.

Koyro, H. W., & Eisa, S. S. (2008). Effect of salinity on composition, viability and germination of seeds of Chenopodium quinoa. *Plant and Soil, 302*(1), 79–90.

Liang, C. (2016). Genetically modified crops with drought tolerance: Achievements, challenges, and perspectives. In M. A. Hossain et al. (Eds.), *Drought stress tolerance in plants, Vol 2: Molecular and genetic perspectives* (pp. 531–547). Springer. https://doi.org/10.1007/978-3-319-32423-4_20

Li, M., Chen, R., Jiang, Q., Sun, X., Zhang, H., & Hu, Z. (2020). GmNAC06, a NAC domain transcription factor, enhances salt stress tolerance in soybean. *Plant Molecular Biology, 105*(3), 333–345. https://doi.org/10.1007/s11103-020-01029-4

Mahmood-ur-Rahman, Ijaz, M., Qamar, S., Bukhari, S. A., & Malik, K. (2019). Abiotic stress signaling in rice crop. In M. Hasanuzzaman et al. (Eds.), *Advances in rice research for abiotic stress tolerance* (pp. 551–569). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-814332-2.00029-2

Marson, M., Saccone, D., & Vallino, E. (2023). Total trade, cereals trade and undernourishment: New empirical evidence for developing countries. *Review of World Economics, 159*, 299–332. https://doi.org/10.1007/s10290-022-00460-6

Mooney, H. A., Hobbs, R. J., Gorham, J., et al. (1986). Biomass accumulation and resource utilization in co-occurring grassland annuals. *Oecologia, 70*(4), 555–558. https://doi.org/10.1007/BF00379975

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

Özkaldı, A., Boz, B., & Yazıcıoğlu, V. (2004). GAP'ta drenaj sorunları ve çözüm önerileri. In *Sulanan Alanlarda Tuzluluk Yönetimi Sempozyumu Bildiriler Kitabı* (pp. 97–106). Ankara, Türkiye.

Pagán, I., & García-Arenal, F. (2018). Tolerance to plant pathogens: Theory and experimental evidence. *International Journal of Molecular Sciences, 19*(3), 810. https://doi.org/10.3390/ijms19030810

Patel, P. R., Kajal, S. S., Patel, V. R., Patel, V. J., & Khristi, S. M. (2010). Impact of saline water stress on nutrient uptake and growth of cowpea. *Brazilian Journal of Plant Physiology, 22*(1), 43–48. https://doi.org/10.1590/S1677-04202010000100006

Pessarakli, M., Tucker, T. C., & Nakabayashi, K. (1991). Growth response of barley and wheat to salt stress. *Journal of Plant Nutrition, 14*(4), 331–340. https://doi.org/10.1080/01904169109364111

Rasheed, M. J. Z., Ahmad, K., Ashraf, M., Al-Qurainy, F., Khan, S., & Athar, H. U. R. (2015). Screening of diverse local germplasm of guar [*Cyamopsis tetragonoloba* (L.) Taub.] for salt tolerance: A possible approach to utilize salt-affected soils. *Pakistan Journal of Botany, 47*(5), 1721–1726.

SAS Institute. (2004). *JMP user's guide: Version 8.01.2*. SAS Institute.

Saxena, N. P., Saxena, M. C., Ruckenbauer, P., Rana, R. S., El-Fouly, M. M., & Shabana, R. (1994). Screening techniques and sources of tolerance to salinity and mineral nutrient imbalances in cool-season food legumes. *Euphytica, 73*(1), 85–94. https://doi.org/10.1007/BF00027191

Shannon, M. C. (1998). Adaptation of plants to salinity. *Advances in Agronomy, 60*, 75–120. https://doi.org/10.1016/S0065-2113(08)60601-X

Shewry, P. R. (2009). Wheat. *Journal of Experimental Botany, 60*(6), 1537–1553. https://doi.org/10.1093/jxb/erp058

Stavridou, E., Hastings, A., Webster, R. J., & Robson, P. R. H. (2017). The impact of soil salinity on the yield, composition and physiology of the bioenergy grass *Miscanthus × giganteus*. *GCB Bioenergy, 9*(1), 92–104. https://doi.org/10.1111/gcbb.12323

Taghipour, F., & Salehi, M. (2008). The study of salt tolerance of Iranian barley (Hordeum vulgare L.) genotypes in seedling growth stages. *Biological Diversity and Conservation, 1*(2), 53–58.

TÜİK. (2024). *TÜİK - Veri Portalı*. https://www.tuik.gov.tr/ (Erişim tarihi: Ocak 2024)

Van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food, 2*(7), 494–501. https://doi.org/10.1038/s43016-021-00322-9

Vardar, Y., Çifci, E. A., & Yağdı, K. (2014). Salinity effects on germination stage of bread and durum wheat cultivars. *Yüzüncü Yıl University Journal of Agricultural Sciences, 24*(2), 127–139.

Wang, W., Vinocur, B., & Altman, A. (2003). Plant responses to drought, salinity and extreme temperatures: Toward genetic engineering for stress tolerance. *Planta, 218*(1), 1–14. https://doi.org/10.1007/s00425-003-1105-5

Yan, W. (2014). *Crop variety trials: Data management and analysis*. John Wiley & Sons. https://doi.org/10.1002/9781118688571