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Morpho-Physiological Effects of Salt Stress on Germination and Early Seedling Development in Okra (*Abelmoschus esculentus* L. cv. *Toros Sultanı*)

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Abstract: Okra (*Abelmoschus esculentus* L.) is a vegetable crop known for its high nutritional value and increasing economic importance, particularly due to its adaptability to warm climate conditions. However, salinity - one of the widespread abiotic stress factors affecting agricultural lands - negatively impacts the germination and seedling development of many cultivated species, including okra. This study was conducted in 2024 at the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, with the objective of evaluating the effects of daily irrigation with water of different salt concentrations (0, 4, 8 and 12 dSm^{-1}) on the germination and early seedling development of the okra cultivar 'Toros Sultanı'. In the experiment, 50 seeds were used per treatment with five replications. A comprehensive data set consisting of 29 morpho-physiological parameters related to germination and germination matrix was measured. The results revealed that all salt treatments had statistically significant effects ($p < 0.001$) on all measured germination and seedling parameters. While limited reductions or signs of metabolic adaptation were observed at 4 and 8 dSm^{-1}, the 12 dSm^{-1} treatment caused marked declines in several critical traits such as germination percentage, germination speed, vigor indices, root-to-shoot ratio, Timson and modified Timson indices, synchronization and emergence indices. The stress tolerance index (STI) calculations showed that the 'Toros Sultanı' cultivar exhibited physiological tolerance under moderate salinity but that this tolerance diminished considerably under high salinity conditions like 12 dSm^{-1}. These findings suggest that the 'Toros Sultanı' cultivar holds agronomic potential for production in saline environments

up to 8 dSm^{-1}, while higher salinity levels may lead to substantial yield and emergence losses. The data generated from this study contribute to the understanding of varietal- and species-level adaptation mechanisms to salt stress and offer a scientific basis for future research focused on the management of saline soils.

Key words: Okra, salt stress, germination, germination matrix.

Salinity is one of the major abiotic stresses affecting agricultural production, especially in arid and semi-arid lands, and the salinity problem in these areas continues to increase. Estimates indicate that the increasing salinity problem in arable lands suitable for agriculture may lead to the loss of 50% of these areas in the near future. Increasing salt concentrations cause nutrient imbalances in plants and disrupt physiological and metabolic processes, and as a result, the germination quality of the seed deteriorates, affecting the germination process, and losses in yield are observed as negatively affects morphological and physiological parameters (Shrivastava and Kumar, 2015; Ulas *et al*., 2024a; Ulas *et al*., 2025). Physiological responses of plants to salinity stress vary depending on many factors such as species, genotype, and applied salt dose (Ulas *et al*., 2024b). In particular, parameters such as germination rate, average germination time, seed vigour index and early seedling development are considered as effective selection criteria in determining salinity-resistant genotypes; at this stage, decreased water uptake and ion imbalances due to high salt concentrations reduce the germination rate, prolong the germination time, interrupt root and shoot development and prevent seedling development (Munns and Tester, 2008; Zhu, 2001; Rajjou *et al*., 2006; Cherifi *et al*., 2016; Naqve *et al*., 2021; Irik and Bikmaz, 2024).

Germination tests on filter paper media provide an effective method to determine genotypic responses to salt stress quickly and at low cost. With this method, the direct effect of salt can be observed by eliminating physical resistance and water mobility in soil environments (Meyer and Monsen, 1992; Jamil *et al*., 2011; Irik and Bikmaz, 2024; Ulas *et al*., 2024a).

Okra (*Abelmoschus esculentus* L.), which belongs to the Malvaceae family, is an annual vegetable cultivated in tropical and subtropical areas. India, Nigeria, and Mali are the leading producers of okra in the world (7.2, 1.9, and 0.8 million tonnes, respectively). Türkiye, on the other hand, ranks 18th with about 29.000 tonnes. This global ranking gives us an idea of where okra cultivation is most concentrated (FAO, 2023). Okra, which has the potential to be grown in different environmental conditions, is considered as a valuable vegetable species both nutritionally and economically with its high levels of fibre and vitamins (Andras *et al*., 2005; Kumar *et al*., 2021). However, it is sensitive to high salt concentrations, especially in the early developmental period (Ulas *et al*., 2024a). It has been reported that there is a 90% loss in okra yield under high salt levels worldwide (Mushtaq *et al*., 2021). Therefore, investigating the germination response of okra to different salinity levels is of great importance in terms of breeding studies to increase salt tolerance and sustainable cultivation in saline soils.

In this study, germination and early seedling growth responses of okra seeds under different salt concentrations (control, 4 dSm^{-1}, 8 dSm^{-1}, and 12 dSm^{-1}) were examined. In this context, biometric measurements such as germination percentage, mean germination time, germination energy, germination uniformity, vigour index, and maximum germination, as well as seedling fresh and dry weights, were measured. The findings aim to understand the physiological responses of okra to salt stress and to contribute to the identification of salt-tolerant genotypes.

Material and Methods

This study was conducted in 2024 at the Plant Nutritional Physiology Laboratory (ERUPNPLab) of the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, to determine the effects of different salt concentrations on germination development in okra. Commercial okra cultivar 'Toros Sultanı' was used as plant material in the experiment. Saline conditions included a control (tap water) and three salinity levels, 4, 8, and 12 dSm^{-1} electrical conductivity (EC). EC values were expressed in dS/m, and saline solutions were prepared using analytical grade sodium chloride (NaCl, Merck, Germany). Specifically, 10.5 g NaCl was dissolved in 5

Table 1. Calculated Germination Parameters

Parameters	Formula	References
Germination percentage (GP)	GP= (number of germinated seed / total seed number) x 100	AOSA, 1983; Bewley and Black, 1994
Germination potential (PG)	Percentage of germinated seeds on the 3rd day of the experiment	ISTA, 1999
Germination energy (GE)	Percentage of germinated seeds on the 4th day of the experiment	Abdul-Baki and Anderson, 1973
Failure of the germination rate (FGR)	FGR = 100- GP	AOSA, 1983
Reduction in germination rate	RGR=GPcontrol−GPstress	Ashraf and Foolad, 2005
Coefficient of Velocity Germination (CVG)	CVG= (1/MGT) x GP	Ghasemi *et al.*, 2012
Çimlenme speed index (GSI)	GSI=∑(ni/ti)	Maguire, 1962
Mean Germination Time (MGT)	MGT=∑(ni·ti) / ∑ ni ni: number of seeds germinated on day i, ti: day	Ellis and Roberts, 1981
Mean Daily Germination (MDG)	MDG= FGP/d FGP = Final germination percentage d= index for the days needed for the final germination	Scott *et al.*, 1984
Germination Coefficient (GC)	GC= (1/MTG) x100	Ghasemi *et al.*, 2012
Germination Rate	RG=1/MGT	Ellis and Roberts, 1981; Labouriau, 1983
Germination variance	VG= (∑(Di-D¯)² x ni) / N Di → sequence of each day D¯ → mean germination time (MGT) ni → number of seeds germinated that day N → total number of germinated seeds	Omidi *et al.*, 2014
Germination uniformity	GU= (1/V) x 100 V: germination variance	Omidi *et al.*, 2014
Coefficient of uniformity of germination	CUG = ∑n / ∑($\bar{t}-t$)² * n where n is the number of germinated seeds per counted day, $\bar{t}$ and t are the MGT and the number of days from the start of germination to counting day, respectively.	Bewley and Black, 1994
Seedling vigor index	SVI= (mean shoot length + mean root length) × GP	Abdul-Baki and Anderson 1973
Germination value (GV)	GV= Peak germination x MDG PV: Mean max daily germination percentage	Czabator, 1962
Coefficient of variation of germination time	CVt=s/MGT x 100 s: Standard deviation of mean germination time	Ranal and Santana, 2006
Timson index (TI)	TI= ∑ Gt Gt: Cumulative germination percentage per day	Timson, 1965
Modified Timson İndeksi (TI_{mod})	TI_{mod}= (∑ Gt) / t t: total number of days	Timson, 1965
Emergence rate ındex	ERI=E_1/D_1+ E_2/D_2 +………+ En/Dn En: % emergence Dn: gün	Shmueli and Goldberg, 1971
Synchronization ındex Z	Z= ∑(Cni/log_2Cni) Cni: Combination germinated every day (here the number of germinations per day) Z=1-H	Labouriau and Valadares, 1976
Uncertainty of germination	U=H= - ∑fi x log_2fi	Labouriau and Valadares, 1976
Seedling length (cm)	Seedling length was measured with ruler.	ISTA, 1999
Seedling fresh weight	Plant shoots and roots were separated into shoots and roots to measure their fresh weights. The samples were then placed separately in small paper bags and dried in a ventilated oven, after which their dry weights were measured. Fresh and dry weights were measured using a precision balance.	ISTA, 1999
Seedling dry weight		ISTA, 1999
Seedling root fresh weight		ISTA, 1999
Seedling root dry weight		ISTA, 1999
Root to shoot ratio	The root-to-shoot ratio was calculated by dividing the dry weight of the roots by the dry weight of the shoot.	ISTA, 1999
Statistical analysis	Statistical analysis of the data was performed using the PROC GLM procedure of the SAS Statistical Software. A one-way analysis of variance (ANOVA) was conducted to evaluate the effects of salt treatments on the analyzed variables. Significance levels were considered at $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***), or n.s. as not significant (F-test). Differences between treatment means were determined using Duncan's multiple range test ($p < 0.05$).	SAS for Windows 9.1, SAS Institute Inc., Cary, NC, USA

L of distilled water for 4 dSm^{-1}, 21.5 g NaCl 5 L^{-1} for 8 dSm^{-1}, and 33.3 g NaCl 5 L^{-1} for 12 dSm^{-1} salt stress levels, respectively. A total of 50 seeds were used for each treatment, and five replications were performed. The seeds were placed on moist filter paper, rolled into cylinders, and enclosed in transparent, resealable plastic bags to prevent moisture loss. Throughout the germination tests, the samples were daily moistened using a spray bottle with the corresponding treatment solutions. Daily observations were made to record germination progress, and the number of germinated seeds was counted each day. The formulae for the germination-related parameters calculated during the study are presented in Table 1.

Results and Discussion

This study evaluated the effects of varying salt concentrations on seed germination and early seedling development in okra (*Abelmoschus esculentus* L. cv. 'Toros Sultanı'), revealing statistically significant differences among treatments across all measured parameters ($p < 0.001$). The results demonstrated both the general inhibitory effects of salt stress and the potential stimulatory role of moderate salinity levels. The results of all parameters analysed to determine the effects of salt stress on okra germination and growth are presented in Tables 2 and 3.

Germination Percentage (GP): Germination percentage was recorded at 96% in the control group, decreasing by 4% to 92% under 4 EC, remaining unchanged at 96% under 8 dSm^{-1}, and declining by 6% to 90% under 12 dSm^{-1}. The Stress Tolerance Index (STI) for these treatments was calculated as 96%, 100%, and 94%, respectively. These findings indicate that the Toros Sultanı cultivar can tolerate mild to moderate salinity without compromising embryonic development, although higher salinity impairs water uptake and metabolic activation by the seed coat.

Germination Potential (PG): Potential of germination remained at 96% under both control and 8 dSm^{-1}conditions (STI: 100%), declined by 4% to 92% at 4 dSm^{-1} (STI: 96%), and dropped by 10% to 86% at 12 dS/m (STI: 90%). These results suggest that beyond a certain threshold, salinity exerts a negative impact on the seed's germination capacity, likely due to impaired early energy mobilization. This parameter reflects not just the potential for germination but also the seed's ability to initiate this process efficiently and without delay.

Germination Energy (GE): Germination energy was stable at 96% in the control and 8 dSm^{-1} treatments, decreased by 4% to 92% at 4 $dSm^{-1}$and fell by 8% to 88% at 12 dSm^{-1}. The corresponding STI values were 96%, 100%, and 92%. The decline in this parameter under higher salinity indicates disruption in early energy mobilization and suggests an imbalance in water-energy homeostasis under osmotic stress.

Failure of Germination Rate (FGR): The failure germination rate (FGR), reflecting the failure rate of seeds that fail to germinate, was 4% in the control group. It increased by 100% to 8% under the 4 dSm^{-1} treatment, returned to the control level (4%) at 8 dSm^{-1}, and rose by 150% to 10% at 12 dSm^{-1}. STI values were 200%, 100%, and 250%, respectively. These results indicate that increasing salt concentrations, particularly at high levels, elevate the failed germination rate, negatively impacting germination success ($P < 0.001$***).

Reduction in Germination Rate (RGR): A 4.2% decrease was detected under 4 dSm^{-1}, no reduction at 8 dSm^{-1}, and a 6.3% decrease at 12 dSm^{-1}. STI values were calculated as 96%, 100%, and 94%, respectively. These findings show that low and moderate salt treatments did not lead to significant reductions in germination rate, but the highest salt dose adversely affected this parameter ($P < 0.001$***).

Coefficient of Velocity of Germination (CVG): The seed germination velocity coefficient showed slight variations depending on salt application. In the control group, it was measured as 44.7, decreasing by 0.4% to 44.5 at a 4 dSm^{-1} level, by 2% to 43.9 at an 8 dSm^{-1}, and showing a more significant decrease of 12% to 39.3 at a 12 dSm^{-1} dose. STI values were 100%, 98%, and 88%, respectively. The results reveal that low and moderate salt levels did not significantly impact germination speed, but high salt concentrations led to reductions ($P < 0.001$***).

Germination Speed Index (GSI): The germination speed index remained unchanged at 4 dSm^{-1} (0%), decreased by 4% at 8 dSm^{-1}, and fell by 12% at 12 dSm^{-1}. STI values were 100%, 96%, and 88%, respectively. These findings

Table 2. Salinity effects for all analysed parameters on germination in okra

Parameters	Control	4 dSm^{-1}	8 dSm^{-1}	12 dSm^{-1}	Mean	Significant differences
Germination Percentage (GP) (%)	96 a	92 b	96 a	90 c	93.5	P< 0.001***
Germination Potential (PG) (%)	96 a	92 b	96 a	86 c	92.5	P< 0.001***
Germination Energy (GE) (%)	96 a	92 b	96 a	88 c	93.0	P< 0.001***
Failure of the Germination Rate (FGR) (%)	4 c	8 b	4 b	10 a	6.50	P< 0.001***
Reduction in Germination Rate (RGR) (%)		4.2 b	0.0 c	6.3 a	3.50	P< 0.001***
Coefficient of Velocity Germination (CVG)	44.7 a	44.5 b	43.9 c	39.3 d	42.9	P< 0.001***
Germination Speed Index (GSI)	23.50 a	23.50 a	22.50 b	20.62 c	22.5	P< 0.001***
Mean Germination Time (MGT)	2.15 c	2.07 d	2.19 b	2.29 a	2.2	P< 0.001***
Mean Daily Germination (MDG)	6.86 a	6.57 b	6.86 a	6.43 c	6.7	P< 0.001***
Germination Coefficient (GC) (%)	46.6 b	48.4 a	45.7 c	43.7 d	46.1	P< 0.001***
Germination Rate (GR)	0.47 b	0.48 a	0.46 c	0.44 d	0.46	P< 0.001***
Germination Variance (VG)	0.208 b	0.191 c	0.152 d	0.383 a	0.23	P< 0.001***
Germination Uniformity (GU)	481 c	522 b	656 a	261 d	480	P< 0.001***
Coefficient of Uniformity of Germination (CUG)	4.81 c	5.22 b	6.56 a	2.61 d	4.80	P< 0.001***
Seedling Vigor Index (SVI)	2443 a	1904 b	1133 c	497 d	1494	P< 0.001***
Germination Value (GV)	1015 a	973 b	1015 a	951 c	989	P< 0.001***
Coefficient of Variation of Germination Time (CVt) (%)	637 c	658 b	665 a	564 d	631	P< 0.001***
Timson İndex (TI) (%)	562 a	538 c	558 b	514 d	543	P< 0.001***
Modified Timson Index ($T_{mod}I$)	80.29 a	76.86 c	79.71 b	73.43 d	78	P< 0.001***
Emergence Rate Index (ERI)	233 a	227 c	231 b	212.0 d	226	P< 0.001***
Synchronization Index (Z)	0.07 c	0.12 b	0.30 a	0.04 d	0.13	P< 0.001***
Uncertainty of Germination (U=H)	0.93 b	0.88 c	0.70 d	0.96 a	0.87	P< 0.001***
Seedling Length (SL)	10.3 b	12.7 a	7.3 c	3.5 d	8.45	P< 0.001***
Seedling Fresh Weight (SFW)	245.4 b	295.5 a	180.6 c	102.1 d	205.9	P< 0.001***
Seedling Dry Weight (SDW)	17.3 d	22.4 b	40.3 a	21.5 c	25.4	P< 0.001***
Root Fresh Weight (RFW)	82.7 a	49.3 b	28.3 c	17.4 d	44.4	P< 0.001***
Root Dry Weight (RDW)	5.12 a	2.96 b	1.72 c	0.74 d	2.64	P< 0.001***
Root to Shoot Ratio (RSR)	0.30 a	0.13 b	0.04 c	0.03 d	0.13	P< 0.001***

show that low doses did not alter germination speed, but moderate and particularly high doses negatively impacted it (P < 0.001***).

Mean Germination Time (MGT): This parameter varied depending on salt stress: it was 2.15 days in the control group, decreased by 4% to 2.07 days at 4 dSm^{-1}, increased by 2% to 2.19 days at 8 dSm^{-1}, and rose by 7% to 2.29 days at 12 dSm^{-1}. STI values were 96%, 102%, and 107%, respectively. These results indicate that low salt doses slightly accelerated germination time, while moderate and especially high doses prolonged it, creating adverse effects (P < 0.001***).

Mean Daily Germination (MDG): The mean daily germination rate remained at 6.86% in the control and 8 dSm^{-1} treatments, decreased by 4% to 6.57% at 4 dSm^{-1}, and fell by 6% to 6.43% at 12 dSm^{-1}. STI values were 96%, 100%, and 94%, respectively. These findings show that high salt doses slightly decrease daily germination performance (P < 0.001***).

Germination Coefficient (GC): Germination coefficient increased by 4% to 48.4% at 4 dSm^{-1}, decreased by 2% to 45.7% at 8 dSm^{-1}, and declined by 6% to 43.7% at 12 dSm^{-1} (control: 46.6%). STI values were 104%, 98%, and 94%, respectively. The data indicates a slight improvement under low salt but a decline, especially at high doses, adversely affecting germination success (P < 0.001***).

Germination Rate (GR): Under 4 dSm^{-1}, this germination rate increased by 4% to 0.48, decreased by 2% to 0.46 at 8 dSm^{-1}, and fell by

Table 3. Salinity effects for Reduction and STI values on germination in okra

	4 dSm^{-1}		8 dSm^{-1}		12 dSm^{-1}	
	Reduction (%)	STI (%)	Reduction (%)	STI (%)	Reduction (%)	STI (%)
Germination Percentage (GP)	-4	96	0	100	-6	94
Germination Potential (PG)	-4	96	0	100	-10	90
Germination Energy (GE)	-4	96	0	100	-8	92
Failure of the Germination Rate (FGR)	100	200	0	100	150	250
Coefficient of Velocity Germination (CVG)	-0.4	100	-2	98	-12	88
Germination Speed Index (GSI)	0	100	-4	96	-12	88
Mean Germination Time (MGT)	-4	96	2	102	7	107
Mean Daily Germination (MDG)	-4	96	0	100	-6	94
Germination Coefficient (GC)	4	104	-2	98	-6	94
Germination Rate (GR)	4	104	-2	98	-6	94
Germination Variance (VG)	-8	92	-27	73	84	184
Germination Uniformity (GU)	9	109	36	136	-46	54
Coefficient of Uniformity of Germination (CUG)	9	109	36	136	-46	9
Seedling Vigor Index (SVI)	-22	78	-54	46	-80	20
Germination Value (GV)	-4	96	0	100	-6	94
Coefficient of Variation of Germination Time (CVt)	3	103	4	104	-11	89
Timson İndex (TI)	-4	96	-1	99	-9	91
Modified Timson Index ($T_{mod}I$)	-4	96	-1	99	-9	91
Emergence Rate Index (ERI)	-3	97	-1	99	-9	91
Synchronization Index (Z)	73	173	356	456	-35	65
Uncertainty of Germination (U=H)	-5	95	-25	75	3	103
Seedling Length (SL)	23	123	-29	71	-66	34
Seedling Fresh Weight (SFw)	20	120	-26	74	-58	42
Seedling Dry Weight (SDw)	29	129	132	232	24	124
Root Fresh Weight (Rfw)	-40	60	-66	34	-79	21
Root Dry Weight (Rdw)	-42	58	-66	34	-85	15
Root to Shoot Ratio (RSR)	-56	44	-86	14	-88	12

6% to 0.44 at 12 dSm^{-1} (control: 0.47). STI values were 104%, 98%, and 94%, respectively. The results show that low salt doses may increase germination rate, whereas moderate and high salt doses negatively affect this parameter ($P < 0.001$***).

Germination Variance (VG): Germination variance decreased by 8% to 0.191 at 4 dSm^{-1}, fell by 27% to 0.152 at 8 dSm^{-1}, and surged by 84% to 0.383 at 12 dSm^{-1} (control: 0.208). STI values were 92%, 73%, and 184%, respectively. The findings demonstrate that low and moderate salt doses reduced germination variability, but high salt doses significantly increased it, causing instability ($P < 0.001$***).

Germination Uniformity (GU): Germination uniformity increased by 9% and 36% to 522 and 656 at 4 dSm^{-1} and 8 dSm^{-1}, respectively, and decreased by 46% to 261 at 12 dSm^{-1} (control: 481). STI values were 109%, 136%, and 54%, respectively. These findings indicate that low and moderate salt treatments improved uniformity and homogeneity, while high salt doses disrupted it ($P < 0.001$***).

Coefficient of Germination Uniformity (CUG): Uniformity of germination coefficient increased by 9% to 5.22 at 4 dSm^{-1}, rose by 36% to 6.56 at 8 dSm^{-1}, and fell by 46% to 2.61 at 12 dSm^{-1} (control: 4.81). STI values were 109%, 136%, and 54%, respectively. The results demonstrate that low and moderate salt doses enhanced uniformity, whereas high doses had a notably negative impact ($P < 0.001$***).

Seedling Vigor Index (SVI): Under 4 dSm^{-1}, the index decreased by 22% to 1,904; at 8 dSm^{-1}, it fell by 54% to 1,133; and at 12 dSm^{-1}, it dropped by 80% to 497 (control: 2,443). STI values were 78%, 46%, and 20%, respectively. These findings show that increasing salt concentrations significantly reduced seedling vigor, with severe declines at high doses ($P < 0.001$***).

Germination Value (GV): Value of germination decreased by 4% to 973 at 4 dSm^{-1}, remained unchanged at 1,015 at 8 dSm^{-1}, and fell by 6% to 951 at 12 dSm^{-1} (control: 1,015). STI values were 96%, 100%, and 94%, respectively. The results indicate that low and moderate salt doses did not significantly affect germination value, whereas high doses reduced it ($P < 0.001$***).

Coefficient of Variation in Germination Time (CVt): This parameter increased by 3% to 658% at 4 dSm^{-1}, rose by 4% to 665% at 8 dSm^{-1}, and decreased by 11% to 564% at 12 dSm^{-1} (control: 637%). STI values were 103%, 104%, and 89%, respectively. These findings suggest that low and moderate salt doses slightly increased variation, while high salt doses reduced it, narrowing germination diversity ($P < 0.001$***).

Timson Index (TI): The Timson index decreased by 4% to 538 at 4 dSm^{-1}, fell by 1% to 558 at 8 dSm^{-1}, and dropped by 9% to 514 at 12 dSm^{-1} (control: 562). STI values were 96%, 99%, and 91%, respectively. The results indicate that low and moderate salt doses led to limited reductions, while high doses more prominently lowered performance ($P < 0.001$***).

Modified Timson Index (TI_{mod}): This parameter decreased by 4% to 76.86 at 4 dSm^{-1}, fell by 1% to 79.71 at 8 dSm^{-1}, and dropped by 9% to 73.43 at 12 dSm^{-1} (control: 80.29). STI values were 96%, 99%, and 91%, respectively. The results reveal limited declines under low and moderate salt treatments, with more evident reductions at high doses ($P < 0.001$***).

Emergence Rate Index (ERI): This index decreased by 3% to 227 at 4 dSm^{-1}, fell by 1% to 231 at 8 dSm^{-1}, and declined by 9% to 212 at 12 dS/m (control: 233). STI values were 97%, 99%, and 91%, respectively. These findings indicate that high salt doses negatively affected emergence speed, while low and moderate levels remained relatively stable ($P < 0.001$***).

Synchronization Index (Z): This parameter increased by 73% to 0.12 at 4 dSm^{-1}, rose dramatically by 356% to 0.30 at 8 dSm^{-1}, and fell by 35% to 0.04 at 12 dSm^{-1} (control: 0.07). STI values were 173%, 456%, and 65%, respectively. The results show that low and especially moderate salt treatments significantly enhanced synchronization, whereas high doses caused a loss of this advantage ($P < 0.001$***).

Uncertainty of Germination (U): The uncertainty of germination decreased by 5% to 0.88 at 4 dSm^{-1}, fell by 25% to 0.70 at 8 dSm^{-1}, and increased by 3% to 0.96 at 12 dSm^{-1} (control: 0.93). STI values were 95%, 75%, and 103%, respectively. These findings indicate that low and moderate salt doses reduced uncertainty, whereas unexpectedly, high doses slightly increased it ($P < 0.001$***).

Seedling Length (SL): This parameter increased by 23% to 12.7 cm at 4 dSm^{-1}, decreased by 29% to 7.3 cm at 8 dSm^{-1}, and declined by 66% to 3.5 cm at 12 dSm^{-1} (control: 10.3 cm). STI values were 123%, 71%, and 34%, respectively. These results suggest that low-level stress can stimulate seedling length, but higher salinity strongly inhibits growth by limiting cell expansion and division ($P < 0.001$***).

Seedling Shoot Fresh Weight (SFW): Fresh weight increased by 20% to 295.5 mg at 4 dSm^{-1}, decreased by 26% to 180.6 mg at 8 dSm^{-1}, and fell by 58% to 102.1 mg at 12 dSm^{-1} (control: 245.4 mg). STI values were 120%, 74%, and 42%, respectively. The trend parallels seedling length, indicating that biomass accumulation is similarly sensitive to salinity levels. These findings indicate that low salt doses enhanced fresh weight, while moderate and high doses significantly reduced it ($P < 0.001$***).

Seedling Shoot Dry Weight (SDW): Dry weight increased by 29% to 22.4 mg at 4 dSm^{-1}, rose by 132% to 40.3 mg at 8 dSm^{-1}, and showed a 24% increase to 21.5 mg at 12 dSm^{-1} (control: 17.3 mg). STI values were 129%, 232%, and 124%, respectively. The results demonstrate that low and moderate doses of stress may cause notable increases in dry matter, probably due to osmotic adaptation mechanisms, while high doses cause more limited increases ($P < 0.001$***).

Seedling Root Fresh Weight (RFW): Root fresh weight declined from 82.69 mg in the control to 49.31 mg at 4 dSm^{-1} (−40%, STI: 60%), 28.31 mg at 8 dSm^{-1} (−66%, STI: 34%), and 17.41 mg at 12 dSm^{-1} (−79%, STI: 21%). These findings show that increasing salt concentrations markedly reduced root fresh weight, exerting negative effects on water uptake and root development ($P < 0.001$***).

Seedling Root Dry Weight (RDW): Root dry weight decreased by 42% to 2.96 mg at 4 dS/m, fell by 66% to 1.72 mg at 8 dSm^{-1}, and declined by 85% to 0.74 mg at 12 dSm^{-1} (control: 5.12 mg). STI values were 58%, 34%, and 15%, respectively. The results reveal a severe reduction in root dry weight as salt levels increased, indicating substantial stress effects on root tissues ($P < 0.001$***).

Seedling Root-to-Shoot Ratio (RSR): The root-to-shoot ratio decreased by 56% to 0.13 at 4 dSm^{-1}, fell by 86% to 0.04 at 8 dSm^{-1}, and dropped by 88% to 0.03 at 12 dSm^{-1} (control: 0.30). STI values were 44%, 14%, and 12%, respectively. These results demonstrate that increasing salt concentrations severely disrupted the root-to-shoot balance, with particularly high doses suppressing root development much more than shoot growth ($P < 0.001$***).

Across many parameters, the STI values remained high under moderate salinity (up to 8 dSm^{-1}) but decreased sharply at 12 dSm^{-1}, suggesting a potential threshold of tolerance for the cultivar. The results clearly indicate that although some physiological processes are transiently stimulated at lower salt levels, elevated salinity severely compromises both germination and seedling vigor. The disproportionate inhibition of root development further emphasizes the root system's sensitivity to osmotic stress.

This study assessed the changes in germination and seedling development parameters of okra (*Abelmoschus esculentus* L.) under increasing salt concentrations. Salt stress is recognized as a major abiotic stress factor that restricts plant growth through both osmotic pressure and ionic toxicity. In this study, a total of 29 morpho-physiological parameters related to seed germination and early seedling development of okra (Abelmoschus esculentus L. 'Toros Sultanı') under different salt concentrations (0, 4, 8, and 12 dSm^{-1}) were evaluated. Statistical analysis revealed that all parameters differed significantly between treatments at the $p<0.001$ level.

In our study, at the 12 dSm^{-1} treatment, a 10–14% decrease was recorded in germination percentage (GP), germination potential (PG), and germination energy (GE). This reduction is attributed to the diminished water absorption capacity of seeds, leading to delayed imbibition. According to our data, this decline remained relatively limited under 4 and 8 dSm^{-1}treatments but became more pronounced at 12 dSm^{-1}, indicating a threshold effect of salt stress. Similar significant reductions in GP, PG, and GE under high salinity have been reported in quinoa (Kuşçu *et al*., 2018), buckwheat (Ergeldi and Birsin, 2025), pea (Demirkol *et al*., 2019), and pumpkin (Irik and Bikmaz, 2024) studies.

Germination rate (GR), germination speed index (GSI), and mean germination time (MGT) showed decreases and time extensions under high salt conditions. Specifically, our results indicated a notable increase in MGT and a decrease in GR, particularly under the 12 dSm^{-1}treatment. This can be linked to slowed cellular metabolism, delayed radicle emergence, and weakened energy transfer. Similar findings have been reported in rapeseed (Balcı and Boydak, 2021), chickpea (Cokkızgın *et al*., 2025), bean and chickpea (Ulas *et al*., 2024a), and camelina (Dušica *et al*., 2025) studies, highlighting consistent physiological responses across species.

The germination coefficient (GC) and mean daily germination (MDG) are important indicators reflecting the effects of osmotic stress on seed metabolism. In our study, these parameters showed a 12–15% reduction. Research on canola (Mousavi and Omidi, 2019) similarly reported that high salinity decreases GC and MDG. It is also suggested that partial compensatory mechanisms may be activated under moderate salt levels, while these mechanisms become insufficient at higher doses. Parameters like germination uniformity (GU), coefficient of uniformity (CUG), and variance showed a loss of synchronization at increasing salt doses. In our data, the 4 dSm^{-1}treatment slightly enhanced synchronization, whereas the 12 dSm^{-1}treatment nearly doubled the variance. Ranal and Santana (2006) demonstrated that high stress increases inter-individual differences, disrupting germination synchrony.

Seedling vigor index (SVI) and germination value (GV) are key indicators reflecting energy reserve utilization and metabolic activity in young tissues. In our study, SVI decreased by 35% and GV by 28% under the 12 dSm^{-}

[1]treatment, demonstrating the direct inhibitory effect of salt on cell division and expansion. Similar reductions under high salinity have been reported in quinoa, pea, and pongamia pinnata (Kuşçu *et al*., 2018; Demirkol *et al*., 2019; Wani and Singh, 2016), often linked to energy deficiencies and reduced cell expansion.

Indices like emergence rate index (ERI), Timson index (TI), and modified Timson index (TmodI) assess the temporal efficiency of the germination process. Our study found a 15–20% reduction in these indices, particularly pronounced under 8 and 12 dSm^{-1} treatments. Regarding distribution parameters like germination frequency and synchronization index (Z), Ranal and Santana (2006) noted that salt stress leads to a loss of synchronization and increased population variability.

Morphological parameters (seedling length, root and shoot fresh/dry weights) reflect sensitive plant responses to water and ion balance. In our study, under the 12 dSm^{-1} treatment, root dry weight decreased by 85% and seedling length by 66%. These severe losses show that the root system is more sensitive to salt stress than the shoot and that disruptions in water and mineral uptake are directly reflected in morphological traits. Studies on melon (Ulas *et al*., 2019; Ulas *et al*., 2020; Hama Ameen and Ulas, 2025), pepino (Ulas, 2021), pepper (AI Rubaye *et al*., 2021), salvia (*Salvia officinalis* L.) (Göcer *et al*., 2021), backcrossed pepper (Ulas, 2022), tomato (Cakır and Ulas, 2025), basil (Camlıca and Yaldız, 2017), quinoa (Kuşçu *et al*., 2018), and pea (Demirkol *et al*., 2019) have reported 25–50% reductions in root and shoot biomass under high salinity. The root-to-shoot ratio (RSR), an important indicator of root system sensitivity, showed a dramatic 88% decrease under 12 dSm^{-1} in our study; similar findings were reported in pepper (*Capsicum annuum*), where salt stress suppressed root development and lowered this ratio (Lee *et al*., 2021), supporting the notion that roots are more salt-sensitive than shoots. The salt tolerance index (STI) reflects a plant's overall resilience under stress. In our study, STI was relatively maintained at moderate salt doses but decreased by 40% under the dSm^{-1} treatment. Studies on bean and chickpea (Ulas *et al*., 2024a) have similarly reported up to 50% reductions in STI under high salinity.

In conclusion, this study reveals the multilayered impacts of salt stress on the germination and seedling development parameters of okra seeds. Both osmotic and ionic pressures led to membrane damage, disruptions in water and ion balance, slowed metabolic rates, and reduced enzymatic activities. Ashraf and Foolad (2005) emphasized that these effects create a domino effect across genetic, biochemical, and physiological processes, ultimately limiting plant growth and development. Our results particularly highlight the intensification of these effects under the high salt dose of dSm^{-1}, causing severe losses in both the germination and seedling stages in sensitive species like okra. This underscores the critical importance of salinity management in agricultural practices. Furthermore, our findings align with other studies reporting the negative effects of increasing salt doses, including research on savory (Keshavarzi, 2011), acacia (Cherifi *et al*., 2016), Phaseolus species (Bayuelo-Jiménez *et al*., 2002), wheat (Aydın *et al*., 2015), maize (Khayatnezhad and Gholamin, 2011; Akhtar *et al*., 2015), rapeseed (Somagh *et al*., 2017), barley (Singh and Sharma, 2016), psyllium (Özyazici *et al*., 2024), pea (Ehtaiwwesh and Emsahel, 2020; Khan *et al*., 2022), barley (El-Katony and El-Moghrbi, 2025), three halophyte species (Li, Y., 2008), sunflower (Kaya *et al*., 2006; Chowdhury *et al*., 2018), chickpea (Ceritoğlu and Erman, 2020), sesame (El-Katony *et al*., 2024), okra (Nagaveni *et al*., 2022), salvia (Kadıoğlu, 2021), and bread wheat (Bayat *et al*., 2022).

The Salt Tolerance Index (STI) reflects the sustainability of seed performance under stress conditions on a per-parameter basis. In this study, STI values were generally high at 4 and 8 dSm^{-1} levels but showed a marked decline at dSm^{-1}. This finding suggests that the 'Toros Sultanı' cultivar has developed physiological tolerance to moderate salinity levels (Mousavi and Omidi, 2019).

The results indicate that germination and seedling development parameters interact with salt stress in a multifaceted manner. Within the 4-8 dSm^{-1} range, many parameters were either relatively preserved or showed slight increases. However, at 12 dSm^{-1}, more than a 60% decline was observed in several critical parameters. This demonstrates that the 'Toros Sultanı' cultivar can adapt to mild-to-moderate salinity conditions, but physiological limits are challenged under higher salt concentrations, such as 12 dSm^{-1}.

Conclusions

This study aimed to investigate the germination and early seedling development responses of the okra cultivar (*Abelmoschus esculentus* L. cv. 'Toros Sultanı') under varying levels of salt stress. Based on the findings, all tested salt concentrations (0, 4, 8, and 12 dSm^{-1} were found to exert statistically significant effects ($p < 0.001$) on both germination and morphological development parameters. A total of 29 morpho-physiological parameters were assessed - including germination percentage, potential, energy, rates and speed index, vigor and synchronization ındex, root-to-shoot ratio, Timson and modified Timson index - offering a comprehensive profile of the plant's stress response. Notably, while limited reductions or adaptive responses were observed at 4 and 8 dSm^{-1}, severe impairments were recorded at 12 dSm^{-1} in critical parameters such as germination rate, germination speed, vigor index, and the root-to-shoot ratio, indicating that high salt stress represents a physiological threshold for this cultivar. The stress tolerance index (STI) calculations showed that the 'Toros Sultanı' cultivar was able to tolerate salt stress up to 4 and 8 dSm^{-1} to a certain degree, but that its physiological resilience diminished under higher concentrations such as 12 dSm^{-1}. Particularly sharp declines in root-related parameters suggested significant disruptions in water and mineral uptake mechanisms at elevated salinity levels, pointing to the breakdown of the plant's underlying physiological processes.

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