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Research Article

Determination of Salinity and Drought Tolerance in Different *Cynodon dactylon* Genotypes

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Abstract: In this study, the effects of salinity (0, 100, 200, 300, 400, and 500 mM NaCl) and drought stress on the germination and seedling development of five *Cynodon dactylon* genotypes (A, B, C, D, and Gobi), collected from different regions of Iğdır Province, Türkiye, were investigated. Analysis of variance showed that both stresses significantly affected the germination percentage, seedling growth, and physiological parameters. Increasing NaCl concentrations drastically reduced normal germination and biomass accumulation, completely inhibiting germination at 400-500 mM levels. Similarly, severe drought stress (75–95% water deficit) substantially decreased plant height, branch number, and biomass, whereas moderate stress (50%) resulted in limited reductions, indicating partial tolerance. Among the genotypes, Gobi showed the highest tolerance to both Stressors, providing greater germination, chlorophyll content, and biomass under adverse conditions. Genotype D also exhibited remarkable drought tolerance, attributed to its robust root system development. In contrast, Genotype A showed the lowest tolerance, with minimal germination and growth under stress conditions. These findings reveal significant genotype-by-environment interactions and confirm Gobi's superior adaptive capacity to salinity and drought stress, suggesting its potential use in breeding programs and for the restoration of marginal lands.

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1. Introduction

C. dactylon is a versatile plant that is highly adaptable to warm climates, capable of rapid spread, and distinguished by its resistance to trampling, drought, and high temperatures (Taliaferro, 2003; Christians, 2011; Yılmaz et al., 2018). It exhibits a wide range of variation in terms of genetic diversity, environmental adaptation, and morphological characteristics (e.g., stem thickness, leaf width) (Taliaferro, 2003). Its ability to propagate through stolons and rhizomes makes it an important species for soil conservation and erosion control (Tan and Çomaklı, 2009). Its widespread use on sports fields, green areas, and as a forage crop also supports this characteristic (Rimi et al., 2011; Mutlu, 2020; Yanık, 2022). Thanks to its ability to form a dense, durable turf layer, it can be harvested up to four times a year, thereby enhancing livestock productivity by providing a high-quality, low-cost source of roughage (Tan and Çomaklı, 2009; Avcıoğlu and Geren, 2012; Gündel et al., 2014). In addition, due to its rich phytochemical content, it is used for medicinal purposes in both traditional and modern applications (Al-Snafi, 2016).

Drought and salinity are among the major abiotic stressors limiting agricultural production, particularly in arid and semi-arid climates (Munns, 2005). Globally, approximately 46% of soils are located in these climatic regions, and about 50% of irrigated land faces salinity problems (Karaoğlu and Yalçın, 2018). In Türkiye, salinity and alkalinity issues are observed across approximately 1 518 722 hectares, corresponding to 5.48% of cultivated agricultural land (Temel and Şimşek, 2011). Specifically in the Iğdır Plain, 39.6% of the 92200 hectares of arable land consists of saline, alkaline, or boron-rich soils, which significantly limit the region's agricultural productivity (Özkutlu and İnce, 1999; Temel and Şimşek, 2011).

Salinity is one of the major environmental stress factors that adversely affect plant growth and crop yield, particularly in regions with limited water resources (Çulha and Çakırlar, 2011; Maiwan et al., 2023; Salih and Abdulrraziq, 2024; Aydınlı et al., 2024). *C. dactylon* species can tolerate salinity levels ranging from 6 to 10 dS m^{-1} and can therefore be utilized in the reclamation of saline soils (Temel and Şimşek, 2011; Singh et al., 2013). However, reductions in plant height are commonly observed in saline soils, while decreases in leaf area occur under saline and alkaline conditions. Moreover, *C. dactylon* is classified as a semi-drought-tolerant species (Zhou et al., 2009; Husmoen et al., 2012; Uddin et al., 2012; Manuchehri and Salehi, 2014). Morphological traits such as a deep root system, thick epidermal layer, and narrow stomatal openings are notable adaptations that enhance drought resistance (Beard, 1989; Zhou et al., 2014). Additionally, the ability of warm-season forage species to continue root development during the summer months contributes to their resilience under drought conditions (Beard, 1973). Therefore, identifying genotypes with high stress tolerance is of great importance (Zhu et al., 2005; Caruso et al., 2008).

Salinity stress adversely affects germination and seedling development by disrupting physiological processes through ion toxicity and osmotic imbalance. This condition can reduce seed viability, delay germination, or even completely inhibit it (Welbaum et al., 1990; Huang and Redmann, 1995; Terzi et al., 2017). Drought, on the other hand, leads to severe reductions in plant growth, development, and yield by impairing physiological and metabolic functions due to decreased soil moisture (Toole et al., 1956). Under such conditions, plants develop adaptive responses, including increased root growth, reduced leaf surface area, decreased stomatal density, and reduced photosynthetic capacity (Kuşvuran et al., 2008).

In turfgrass species, salinity generally restricts germination and seedling development. Studies on *C. dactylon* have shown that this species exhibits moderate salt tolerance. Tromble (1963) reported that Cynodon seeds germinated even under 180 mM NaCl. Ackerson and Youngner (1975) demonstrated that increasing salinity levels can restrict shoot development while enhancing root growth. Johnson et al. (2007) also reported that seeds can germinate under low to moderate salinity levels. Sarıca (2014) and Çakici and Güneş (2018) emphasized that salinity particularly reduces root and shoot biomass during seedling development, while Pessarakli and Touchane (2006) showed that shoot dry weight decreases with increasing salinity in Cynodon cultivars. Similarly, Hameed and Ashraf (2008) reported that ecotypes from different habitats exhibit variation in salinity tolerance.

Similarly, *C. dactylon* shows varying tolerance to drought stress during the seedling stage. Mutlu (2020) and Zhang et al. (2023a) reported that the Tifway and Survivor cultivars possess high drought tolerance and regeneration capacity. Zhang et al. (2023b) highlighted inter-cultivar differences in nitrogen metabolism under drought conditions, while Lingshuang et al. (2020) and Noor et al. (2024) demonstrated that drought negatively affects plant growth and leaf chlorophyll content. Zhang et al. (2011) indicated that *C. dactylon* can tolerate 8–12 days of drought stress and recover afterward. Moreover, several studies have shown strong relationships among irrigation levels, turf quality, and water-use efficiency (Beard et al., 1992; Bijanzadeh et al., 2013; Zhou et al., 2013).

This study aims to determine how four *C. dactylon* genotypes and the Gobi variety, collected from different ecological regions of Iğdır province in Türkiye, respond to salinity (NaCl) and drought stress during germination and early seedling development. The study also aims to elucidate the effects of these stresses on germination percentage, seedling development characteristics, and selected morphological parameters, and to compare inter-genotype differences in stress tolerance.

2. Materials and Methods

The plant material of this study consisted of *C. dactylon* (L.) Pers. seeds collected from four different natural habitats in Iğdır Province, along with the Gobi cultivar. The genotypes were collected from the following locations: Suveren Village in Iğdır Central District (A), Melekli Town (B), Aşağı Çamurlu Village in Aralık District (C), and Kazımkarabekir Agricultural Enterprise Directorate (TİGEM, D). These local genotypes were used in saline water germination, salinity, and drought stress experiments conducted within the scope of the study.

In this study, the germination performance of *C. dactylon* seeds under saline conditions and their tolerance levels to salinity and drought during the seedling stage were investigated. To break dormancy, seeds were kept at 10 °C for one week, after which germination experiments were conducted at 20/30 °C. Germination was carried out using solutions containing 0, 100, 200, 300, 400, and 500 mM NaCl. The NaCl solutions were prepared by diluting a 1 M stock solution (Delatorre-Herrera and Pinto, 2010). For each population, 25 sterilized seeds were placed in 120 × 20 mm Petri dishes with four replications, and the germination process was monitored in a cooled incubator at different NaCl concentrations.

To determine salinity and drought tolerance at the seedling stage, garden soil mixed with 10% burned farmyard manure was used. The chemical and physical properties of the soil were analyzed at the Soil, Fertilizer and Water Resources Central Research Institute of the Ministry of Agriculture and Forestry (Ankara) and the Eastern Anatolia Agricultural Research Institute (Erzurum).

The experiments were conducted in a glass greenhouse using No. 5 pots (34 cm in diameter, 28 cm in depth, 13 L capacity). Saline water treatments ranging from 0 to 500 mM NaCl (0, 100, 200, 300, 400, and 500 mM) were applied, with three replications per treatment, for a total of 90 pots. Three seeds were sown per pot at a depth of 1 cm. Seeds and seedlings were irrigated with distilled water until the onset of the salinity treatment; after emergence, only one seedling per pot was retained, and the others were removed. Ten days after emergence, saline water treatments were initiated. Salt concentration was gradually increased by 50 mM per day until the target level was reached, after which it was maintained at that level. Soil moisture in each pot was monitored using a moisture meter, and irrigation was applied when available water decreased to 27.9% (Hariadi et al., 2011; Shabala et al., 2013). After 60 days of growth, plants were harvested, and morphological parameters, including plant height, number of tillers, chlorophyll content (measured with a chlorophyll meter), stem diameter, and root length, were recorded. Roots and shoots were separated to determine root dry weight, total plant dry weight, root-to-shoot dry weight ratio, and salt tolerance percentage (STP) (Sanchez et al., 2003; González et al., 2009; Ruiz-Carrasco et al., 2011; Adolf et al., 2012; Raney et al., 2014). At the end of the experiment, soil samples were collected from each pot for EC and pH analysis.

Table 1. Basic properties of the soil

Property	Value
pH	7.31
EC (dS/m)	3.58
Salinty (%)	0.835
Lime (%)	5.3
Organic Matter (%)	2.86
P_2O_5 (kg/da)	56.9
K_2O (kg/da)	1068.9
Ca (mg/kg)	2897.5
Mg (mg/kg)	383.5
Fe, Cu, Mn, Zn (mg/kg)	5.47, 1.30, 3.22, 3.20
Pb, Co, Cr, Ni (ppm)	150.9, 7.0, 35.2, 50.4
Texture	Clay Loam
Bulk Density (g/cm^3)	1.49
Field Capacity / Wilting Point (%)	27.9 / 14.23
Available Water (%)	13.67

To assess drought tolerance at the seedling stage, soil preparation, sowing, and thinning were carried out using the same procedures as in the salinity experiment. Ten days after seedling emergence, different drought stress treatments were initiated. Irrigation was applied when 25% (control), 50% (mild drought), 75% (moderate drought), 90% (severe drought), and 95% (extreme drought) of the available soil water had been depleted, restoring the soil to field capacity after each irrigation event (Hariadi et al., 2011).

Table 2. Number of irrigations and amount of water applied (mL) in the drought experiment

Drought Level	Number of	Amount of Water Applied per Irrigation (mL)
Control (25%)	6	484.19
Mild Drought (50%)	4	968.38
Moderate Drought	3	1452.75
Severe Drought (90%)	2	1741.39
Extreme Drought (95%)	2	1837.67

To test drought tolerance, 75 pots were used, with three replications per drought level. Soil moisture levels were monitored with a soil moisture meter, and the soil's water-holding capacity was determined from fresh and dry weight measurements. At the end of the experiment, plant height, number of tillers, root length, chlorophyll content, and fresh and dry weights were measured. Additionally, the root-to-shoot dry weight ratio and drought tolerance percentage (DTP) were calculated (Ruiz-Carrasco et al., 2011; Shabala et al., 2013; Raney et al., 2014).

In this study, various measurements were conducted to determine the morphological and physiological responses of *C. dactylon* plants under stress conditions. Plant height was measured as the distance from the crown to the tip of the longest shoot, while root length was determined as the distance from the crown to the tip of the root. Stem diameter was measured 5 cm above the crown using a digital caliper, and the number of tillers was determined as the total number of first-order lateral shoots and stolons emerging from the main stem.

Chlorophyll content was measured nondestructively on three selected leaves per plant using a SPAD 502Plus chlorophyll meter. Soil pH was determined potentiometrically with a glass electrode pH meter in a 1:2.5 soil-to-water suspension (McLean, 1982), while electrical conductivity (EC) was measured in extracts obtained from saturated soil pastes (Rhoades, 1982).

Fresh shoot weights were measured immediately after cutting at the crown, whereas dry weights were obtained by drying the samples in open air and then in an oven at 70 °C until a constant weight was reached. The same procedure was applied for root fresh and dry weights.

The root-to-shoot dry weight ratio (%) was calculated as: Root-to-shoot dry weight ratio = (Root dry weight/Shoot dry weight) x 100, The salt tolerance percentage (STP) was calculated based on the ratio of dry weights of salt-treated plants to those of the control group as follows: STP = (Dry weight of salt-treated plants/Dry weight of control plants) x 100 (Sanchez et al., 2003; Hariadi et al., 2011; Adolf et al., 2012).

The data obtained from the study were analyzed using analysis of variance (ANOVA) based on a randomized factorial experimental design in JMP 5.0.1. Mean comparisons and groupings for parameters showing significant differences in the ANOVA were performed using the Least Significant Difference (LSD) test.

3. Results

According to the results of the variance analysis, salinity had highly significant effects on total, normal, and abnormal germination rates, as well as on mortality rates. Similarly, the effect of location was significant, indicating that environmental conditions play a crucial role in plant development. During the seedling stage, morphological parameters, including plant height, root length, number of tillers, and fresh and dry weights, were significantly affected by both salinity and drought stress. In particular, parameters related to root development were influenced by both stress factors. Chlorophyll content was more affected by salinity, while its sensitivity to drought was relatively limited. Tolerance percentages for salinity and drought varied among locations, highlighting the importance of genotype–environment interactions. Regarding soil properties, EC values increased significantly under saline conditions, whereas soil pH showed no notable change. Overall, these findings demonstrate that salinity stress exerts strong inhibitory effects on germination and seedling development, while drought stress primarily restricts plant growth. Furthermore, it was concluded that selecting appropriate locations is a critical factor for enhancing stress tolerance.

Table 3. Analysis of variance results

Parameters	**Location (L)**	**Salinity (S)**	**L × S Interaction**	**Drought (D)**	**L × D Interaction**
Seed Normal Germination (%)	115.06**	1383.35**	32.41**	–	–
Seed Abnormal Germination (%)	3.84 ns	24.60**	2.24 ns	–	–
Seed Mortality Rate (%)	97.25**	1481.32**	30.38**	–	–
Plant Height (cm)	426.21** / 208.32**	21.36**	10.07**	53.58**	7.08**
Root Length (cm)	341.07** / 6.44**	926.46**	362.93 ns	6.78**	5.08**
Stem Diameter (mm)	90.98** / 9.91**	8.37**	11.40**	37.62**	0.98 ns
Number of Branches (no./plant)	30.12** / 25.79**	13.18**	2.25**	110.30**	7.47**
Chlorophyll Content (SPAD)	3.72** / 0.53 ns	113.51**	4.38**	1.28 ns	1.21 ns
Shoot Fresh Weight (g)	29.58** / 2.17 ns	174.45**	6.66**	65.39**	1.32 ns
Shoot Dry Weight (g)	8.47** / 2.52*	31.46**	3.73**	52.63**	6.50**
Root Fresh Weight (g)	101.82** / 23.14**	259.38**	18.61**	23.47**	5.46**
Root Dry Weight (g)	84.96** / 18.63**	58.72**	7.50**	21.88**	2.43 ns
Root/Shoot Dry Weight Ratio (%)	43.69** / 13.61**	3.52**	2.57**	0.60 ns	1.04 ns
Salt Tolerance (%)	6.71**	0.23 ns	1.62 ns	–	–
Drought Tolerance (%)	6.37**	–	–	21.97**	3.91**
Electrical Conductivity (dS m^{-1})	8.22**	871.23**	5.50**	–	–
pH	0.55 ns	1.06 ns	1.64 ns	–	–

ns = not significant ($p > 0.05$), * = $p < 0.05$, ** = $p < 0.01$.

Normal, abnormal germination, and seed mortality rates obtained from *C. dactylon* seeds collected from different locations (A: Suveren, B: Melekli, C: Aşağı Çamurlu, D: TİGEM) under varying salt concentrations, as well as the effects of salinity and drought stresses applied during the seedling stage, were compared. Statistically significant differences were observed among treatments and genotypes in the seeds' responses (Tables 4, 5, and 6).

The Gobi genotype was evaluated under different salinity (0–500 mM) and drought (%50–95) treatments. The results revealed statistically significant differences in germination and seedling development among both genotypes and treatments. The Gobi genotype exhibited the highest normal germination rate (28.3%) and the lowest dead-seed rate (71.5%), demonstrating superior seedling growth performance even under saline conditions. In particular, its longer plant height (70.6 cm), higher fresh and dry biomass, chlorophyll content, and tolerance indices at the seedling stage indicate a strong adaptive capacity to stress conditions. Although the D genotype (TİGEM) had a lower germination rate than Gobi, it showed robust performance in branch number, root length, and fresh/dry root weight, suggesting a notable drought tolerance potential. The B (Melekli) and C (Aşağı Çamurlu) genotypes displayed moderate stress tolerance, maintaining relatively balanced performance during both germination and the seedling stage, but lagging behind the Gobi and D genotypes. In contrast, the A genotype (Suveren) exhibited the weakest response to stress, with the lowest normal germination rate (11.3%) and the highest dead seed rate (87.7%) (Table 4). Increasing NaCl concentrations significantly reduced the normal germination rate; it decreased from 59.23% under control conditions to 5.0% at 300 mM and was completely inhibited at 400–500 mM (0%). Parallel to this, the dead seed rate reached 100% at concentrations of 400 mM or higher, compared with 40.8% in the control group (Table 5). Concurrent with these findings, significant reductions were observed in seedling traits, including plant height, root length, fresh and dry weight, and branch number. The highest seedling performance was obtained under non-saline control conditions, whereas plant growth was almost completely inhibited under highly saline environments such as 500 mM NaCl (Table 5). Similarly, under drought stress, plant growth parameters declined with increasing water deficit. Significant reductions in fresh and dry weight, branch number, and plant height were observed, particularly at 75%, 90%, and 95% of the drought levels. However, the 50% drought treatment produced results very similar to those of the control group, indicating that the plant possesses a certain level of adaptability to moderate water scarcity. The highest drought tolerance (99.17%) was observed under the 50% treatment (Table 6).

In the evaluation of *C. dactylon* genotypes, the Gobi genotype exhibited the highest tolerance to both salinity and drought stress, with superior values for germination rate, plant height, chlorophyll content, and biomass. Among the A, B, C, and D genotypes, the D genotype showed the highest resistance, while the A genotype exhibited the lowest resistance. Increasing salinity levels caused a marked reduction in germination, growth, and biomass, and germination completely ceased at concentrations above 300 mM. Under drought conditions, increasing water deficit (75–95%) reduced plant height, branch number, and fresh and dry weights, while chlorophyll content remained largely stable. In conclusion, our study confirms that stress tolerance exhibits genetically distinct variability among *C. dactylon* genotypes; the Gobi genotype, in particular, stands out as a superior candidate for disadvantaged and stress-prone environments (Tables 4, 5, and 6).

Table 4. Responses of different *C. dactylon* genotypes to salinity (S) and drought (D) stress

Genotypes	**Normal Germination (%)**	**Abnormal Germination (%)**	**Dead Seed (%)**	**Plant Height (cm) (S/D)**	**Root Length (cm) (S/D)**	**Stem Diameter (mm) S/D)**	**Branch Number (per plant) (S/D)**	**Chlorophyll (SPAD) (S/D)**	**Fresh Weight (g) (S/D)**	**Dry Weight (g) (S/D)**	**Root Fresh Weight (g) (S/D)**	**Root Dry Weight (g) (S/D)**	**Root DW/Plant DW (%) (S/D)**	**S/D Tolerance (%)**	**EC (dS m^{-1})**	**pH**
Loc. A	11.3 ±0.57 d	1.0 ±0.31 ab	87.7 ±0.59a	31.7 c / 44.3b	50.3 b / 64.1 a	1.7 b / 1.44 a	47.2 ab / 43.9 b	27.6 ab / 31.2	16.3 b / 35.9 a	7.3 b / 13.7 a	7.7 a / 7.8 a	4.19 a / 4.80 a	57.3 a / 35.3 a	48.3 c / 63.97 b	6.2 a	8.5
Loc. B	19.23 ±0.57 b	1.0 ±0.31 ab	79.8 ±0.59 c	32.4 c / 41.1 c	50.8 b / 58.7 bc	1.6 c / 1.46 a	42.2 c / 42.1 b	26.7 bc / 30.6	16.4 b / 30.2 b	7.3 b / 11.9 b	7.4 a / 7.1 ab	3.74 b / 4.2 ab	52.9 ab / 35.5 a	70.1 ab / 80.79 a	5.4 b	8.5
Loc. C	16.8 3 ±0.57 c	1.3 ±0.31 a	81.8 ±0.59 b	32.1 c / 44.1 b	49.2 b / 58.7 bc	1.7 ab / 1.45 a	43.5 bc / 36.5 c	27.1 a-c / 29.5	15.5 b / 29.2 b	6.9 b / 11.7 b	6.8 ab / 7.0 ab	3.30 c / 4.2 ab	48.6 b / 36.8 a	69.8 ab / 87.45 a	5.6 b	8.4
Loc. D	19.53 ±0.57 b	1.8 ±0.31 a	78.7 ±0.59 c	36.9 b / 45.0 b	49.3 b / 61.0 ab	1.8 a / 1.44 a	47.7 a / 47.07 a	26.4 c / 30.9	20.1 a / 32.5 ab	8.6 a / 12.1 b	7.2 b / 6.7 b	4.1 ab / 4.1 b	48.5 b / 34.9 a	63.9 b / 63.53 b	5.5 b	8.4
Gobi	28.33 ±0.57 a	0.2 ±0.31 b	71.5 ±0.59 d	58.2 a / 70.6 a	54.6 a / 55.6 c	1.4 d / 1.30 b	28.3 d / 34.9 c	28.0 a / 29.8	19.3 a / 30.2 b	8.7 a / 12.4 ab	2.6 c / 3.31 c	1.38 d / 2.2 c	16.3 c / 18.1 b	81.9 a / 63.18 b	6.0 a	8.4

A loc: Suveren. B loc: Melekli. C Loc: Aşağı çamurlu. D Loc: TİGEM. Values followed by different letters (a, b, c, d, e) within a column indicate significant differences. EC: Electrical Conductivity; DW: Dry Weight; KA: Dry Weight; S (Salinity)/D (Drought) values are separated by a slash (/).

Table 5. Average values by salinity levels on *C. dactylon*

Salinity (mM)	Normal Germination (%)	Abnormal Germination (%)	Dead Seed (%)	Plant Height (cm)	Root Length (cm)	Stem Diameter (mm)	Branch Number	Chlorophyll (SPAD)	Plant Fresh Weight (g)	Plant Dry Weight (g)	Root Fresh Weight (g)	Root Dry Weight (g)	Root DW/Plant DW (%)	Tolerance (%)	EC (dS m^{-1})	pH
Control	59.23 ±0.63 a	4.2 ±0.34 a	40.8 ±0.65 e	40.5 ±0.6 a	57.9 ±0.98 a	1.7 ±0.02 ab	52.5 ±1.58 a	33.5 ±0.36 a	27.4 ±0.42 a	11.0 ±0.31 a	13.5 ±0.23 a	5.2 ±0.14 a	48.2 ±2.7 ab	–	0.3 f	8.6
100 mM	42.6 ±0.63 b	1.8 ±0.34 b	57.4 ±0.65 d	40.1 ±0.6 a	50.2 ±0.98 b	1.6 ±0.02 cd	43.6 ±1.58 b	29.9 ±0.36 b	19.5 ±0.42 b	8.5 ±0.31 b	6.3 ±0.23 b	3.7 ±0.14 b	46.4 ±2.7 ab	55.5	3.0 e	8.3
200 mM	13.8 ±0.63 c	0.4 ±0.34 c	86.2 ±0.65 c	41.5 ±0.6 a	48.5 ±0.98 b	1.6 ±0.02 cd	39.8 ±1.58 bc	26.7 ±0.36 c	17.3 ±0.42 c	6.8 ±0.31 cd	5.3 ±0.23 c	2.8 ±0.14 cd	42.8 ±2.7 bc	44.8	5.0 d	8.3
300 mM	5.0 ±0.63 d	0.0 ±0.34 c	95.0 ±0.65 b	37.1 ±0.6 b	49.7 ±0.98 b	1.7 ±0.02 a	39.5 ±1.58 bc	24.5 ±0.36 d	13.9 ±0.42 d	6.2 ±0.31 d	5.2 ±0.23 c	3.1 ±0.14 c	51.4 ±2.7 a	49.9	6.9 c	8.5
400 mM	0.0 ±0.63 e	0.0 ±0.34 c	100.0 ±0.65 a	35.8 ±0.6 bc	49.5 ±0.98 b	1.7 ±0.02 ab	38.5 ±1.58 c	24.7 ±0.36 d	14.5 ±0.42 d	6.9 ±0.31 cd	3.8 ±0.23 d	2.7 ±0.14 d	42.7 ±2.7 bc	48.7	8.3 b	8.3
500 mM	0.0 ±0.63 e	0.0 ±0.34 c	100.0 ±0.65 a	34.7 ±0.6 c	49.3 ±0.98 b	1.6 ±0.02 d	36.7 ±1.58 c	23.7 ±0.36 d	12.4 ±0.42 e	7.1 ±0.31 c	3.9 ±0.23 d	2.4 ±0.14 d	37.0 ±2.7 c	42.4	10.9 a	8.6

Values followed by different letters (a, b, c, d, e, f) within a column indicate significant differences. EC: Electrical Conductivity; DW: Dry Weight.

Table 6. Average values by drought levels on *C. dactylon*

Drought	Plant Height (cm)	Root Length (cm)	Stem Diameter (mm)	Branch Number	Chlorophyll (SPAD)	Plant Fresh Weight (g)	Plant Dry Weight (g)	Root Fresh Weight (g)	Root Dry Weight (g)	Root DW/Plant DW (%)	Tolerance (%)
Control	55.4 ±0.84 a	60.5 ±1.24 b	1.62 ±0.21 a	53.5 ±1.0 a	28.5 ±0.98 b	50.2 ±1.83 a	16.4 ±0.49 a	9.4 ±0.36 a	5.5 ±0.23 a	34.1	–
50%	55.6 ±0.84 a	55.6 ±1.24 c	1.45 ±0.21 b	51.1 ±1.0 a	30.5 ±0.98 ab	44.3 ±1.83 b	15.9 ±0.49 a	6.2 ±0.36 b	4.6 ±0.23 b	30.4	99.17 ±4.08 a
75%	46.9 ±0.84 b	64.1 ±1.24 a	1.40 ±0.21 bc	35.7 ±1.0 b	30.4 ±0.98 ab	25.8 ±1.83 c	9.8 ±0.49 bc	5.1 ±0.36 c	3.1 ±0.23 c	32.7	60.35 ±4.08 bc
90%	44.9 ±0.84 b	57.7 1.24 bc	1.33 ±0.21 cd	33.3 ±1.0 bc	31.4 ±0.98 a	21.0 ±1.83 cd	10.9 ±0.49 b	5.8 ±0.36 bc	3.4 ±0.23 c	30.5	70.47 ±4.08 b
95%	42.3 ±0.84 c	60.3 ±1.24 b	1.28 ±0.21 d	30.9 ±1.0 c	31.0 ±0.98 ab	16.8 ±1.83 c	8.9 ±0.49 c	5.3 ±0.36 bc	3.0 ±0.23 c	33.0	57.15 ±4.08 c

Values followed by different letters (a, b, c, d) within a column indicate significant differences. DW: Dry Weight.

The parameters showing statistically significant interaction effects in Table 3 are presented in Figures 1, 2, 3, 4, 5, and 6.

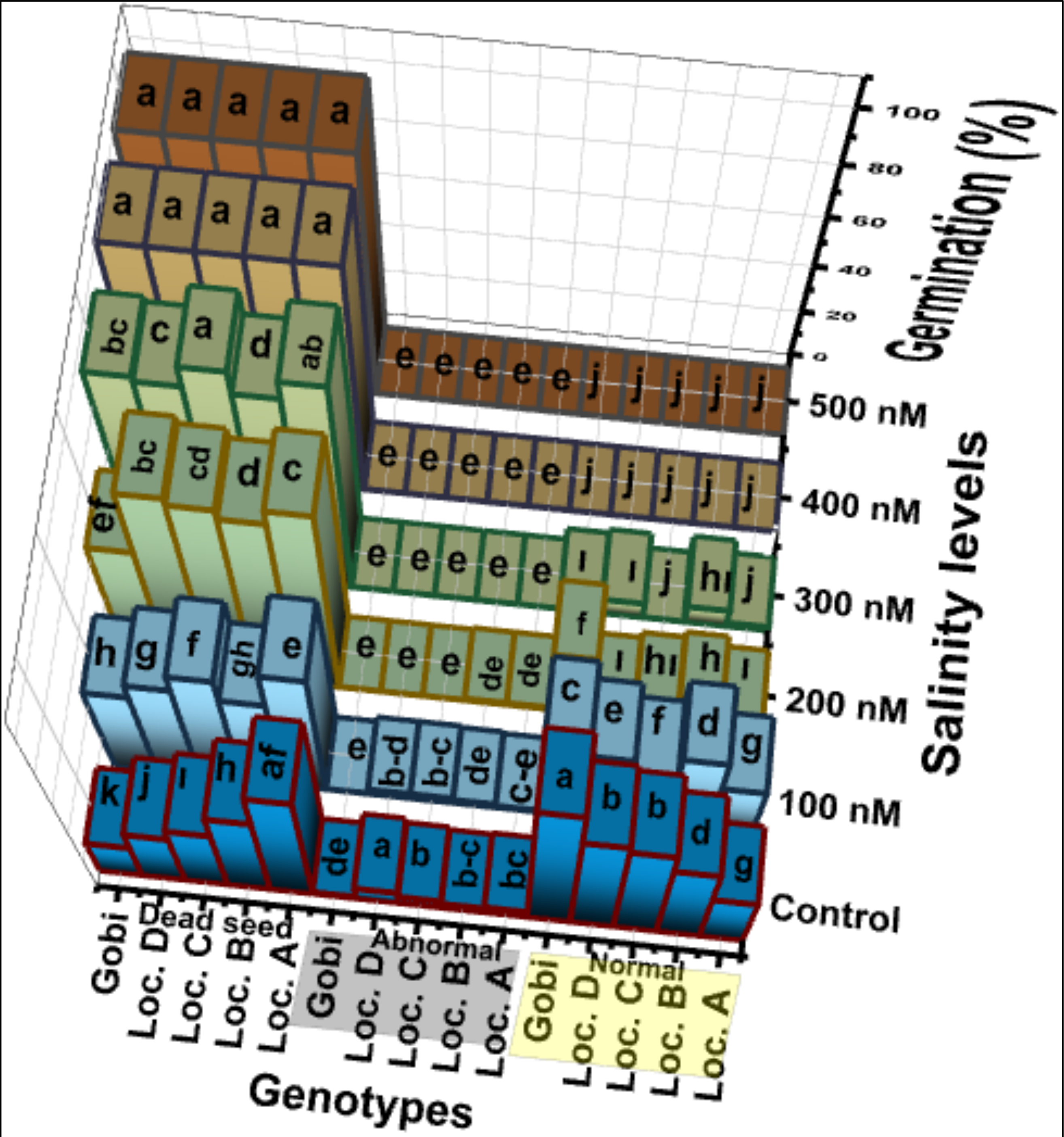

Figure 1. The effect of salinity levels on the germination and dead seed rates (%) of C. dactylon.

When examining the germination responses of four *C. dactylon* genotypes (A, B, C, D) and the Gobi variety under NaCl concentrations ranging from 0 to 500 mM, it was observed that the normal germination rate sharply decreased in all genotypes as salinity increased, with germination almost completely inhibited at 300 mM and higher levels. The highest germination rate was recorded in the Gobi genotype under control conditions (78%). Abnormal germination remained low (0–8%), whereas the dead seed rate rapidly increased with salinity, reaching 100% at 400 mM and above. These findings indicate that increasing salinity severely suppresses seed viability and germination capacity (Figure 1).

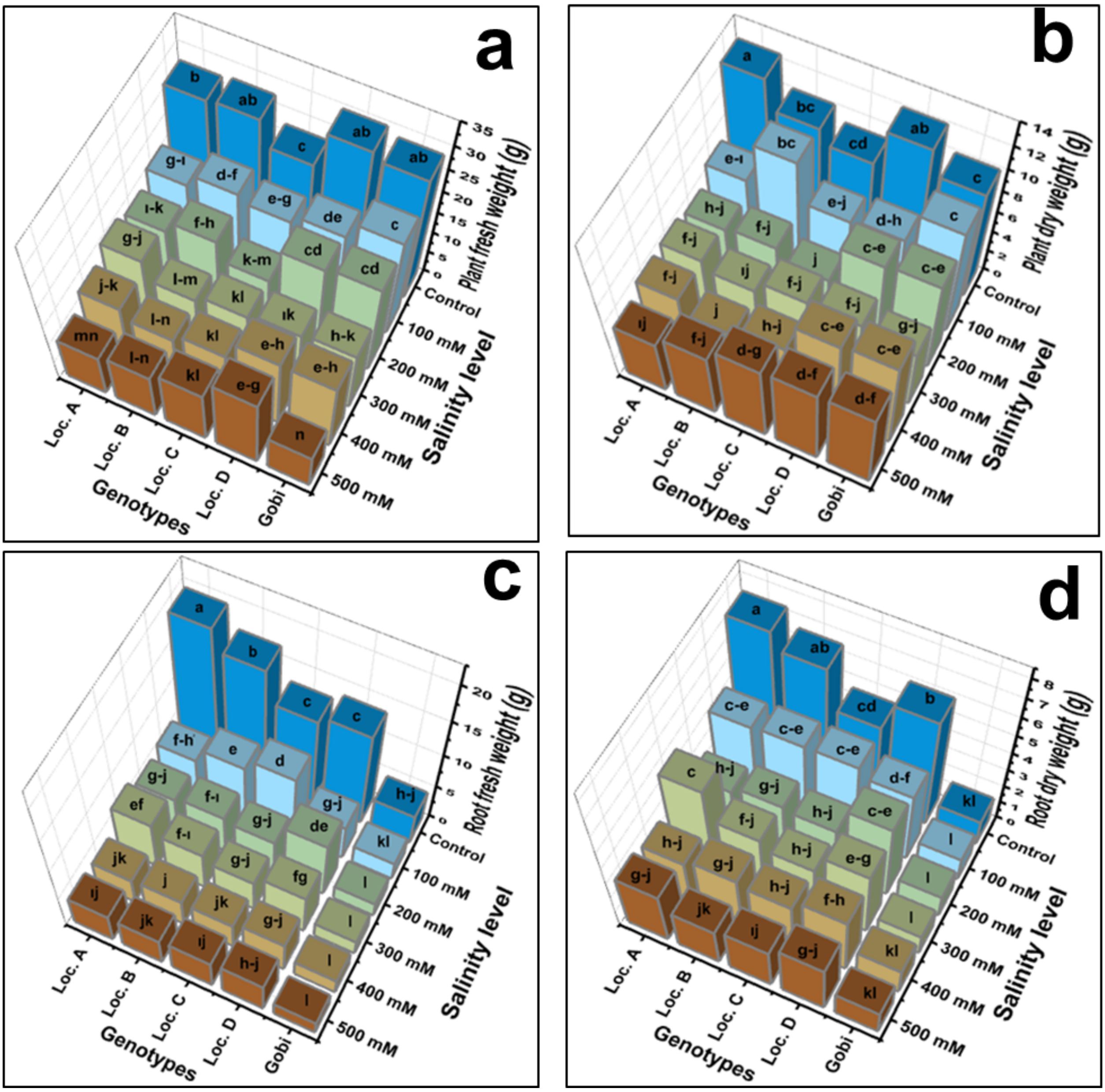

Figure 2. Effects of different salinity levels on the shoot fresh–dry (a, b) and root fresh–dry (c, d) weights of *C. dactylon* genotypes.

When the data for plant fresh weight (a), plant dry weight (b), root fresh weight (c), and root dry weight (d) parameters of *C. dactylon* genotypes were examined, it was observed that both plant and root biomass (Plant and Root Biomass) decreased markedly with increasing salinity levels. Under control conditions, plant fresh weight ranged from 22.7 to 30.3 g, while dry weight ranged from 9.23 to 12.77 g. At 500 mM NaCl concentration, these values declined to 9.17–17.8 g and 5.4–8.0 g, respectively. Similarly, root fresh weight decreased from 12.7–19.7 g to 2–4 g, and root dry weight dropped from 7.4–6.6 g to 1.2–3.0 g. The highest biomass values were recorded in Location D under control conditions, whereas the lowest were observed in the Gobi genotype under high salinity stress (Figure 2).

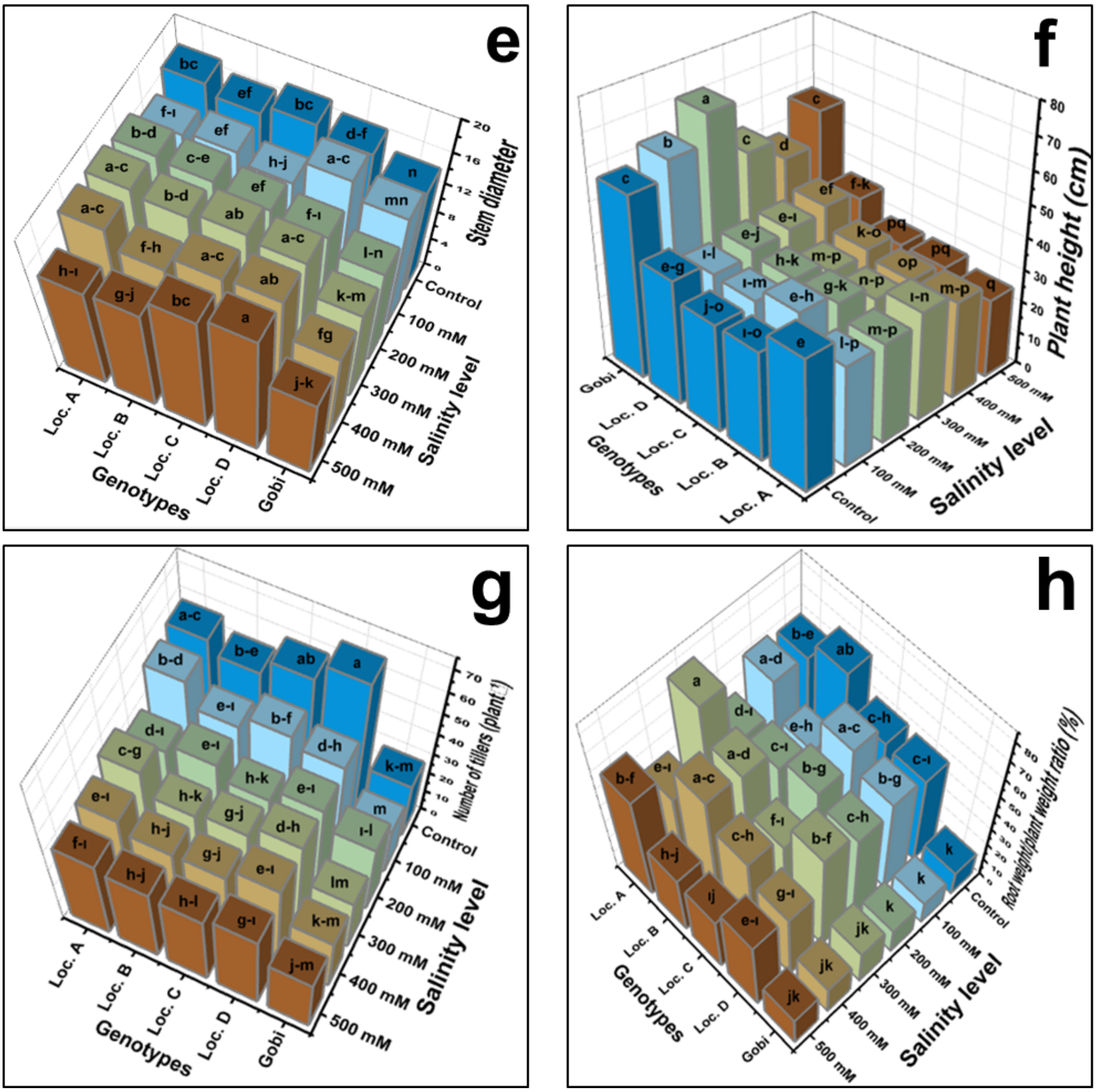

Figure 3. Effects of different salinity levels on stem diameter (e), plant height (f), number of branches (g), and root-to-shoot weight ratio (h) of *C. dactylon* genotypes.

Morphological Responses of *C. dactylon* Genotypes – Increasing salinity levels generally had adverse effects on plant morphological development. Plant height decreased across all genotypes; under control conditions, it ranged from 33 to 57 cm, whereas at 500 mM NaCl, it declined to 25–39 cm. Although the Gobi genotype maintained its height growth under mild salinity (200 mM), a pronounced reduction was observed at higher concentrations. Stem diameter remained relatively stable against salt stress, and notably, the Location D genotype retained its structural integrity, reaching up to 18.7 mm even at 500 mM salinity. The number of tillers decreased markedly with increasing salinity; values ranging from 52 to 67 under control conditions declined to 36–40 under high salinity. The Gobi genotype exhibited the lowest values for this parameter. The root-to-shoot weight ratio varied among genotypes; while root development was relatively maintained in Location A under stress conditions (77.8%), it remained low in the Gobi genotype (13–20%). Overall, these findings indicate that salinity stress limits plant growth and tillering, whereas certain genotypes can partially preserve their structural characteristics (Figure 3).

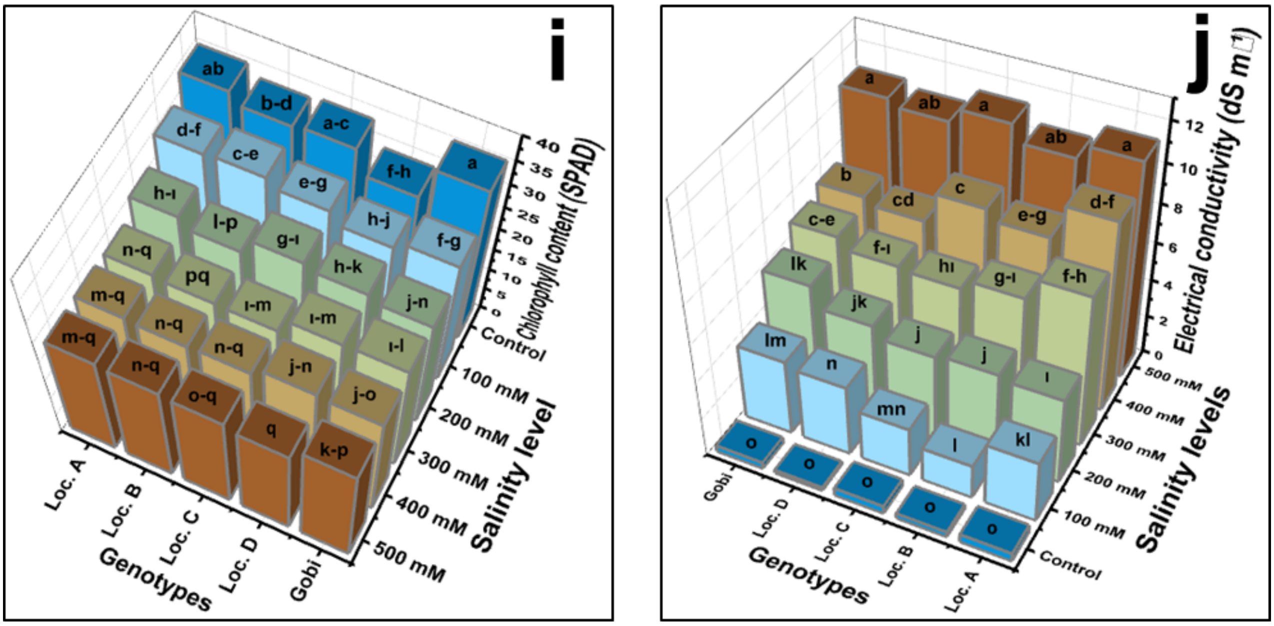

Figure 4. Effects of different salinity levels on chlorophyll content (SPAD) (i) and electrical conductivity (dS m^{-1}) (j) of *C. dactylon* genotypes.

When the chlorophyll content (i) and electrical conductivity (j) values were examined, a consistent decline in chlorophyll content was observed with increasing salinity levels. Under control conditions, chlorophyll values ranged between 29 and 36 SPAD, whereas at 500 mM NaCl, they decreased to 22–25 SPAD. The highest chlorophyll content was recorded in the Gobi genotype under control conditions (35.77 SPAD), while the lowest value was observed in Location D (22.17 SPAD). This reduction is associated with the inhibition of chlorophyll synthesis and the acceleration of pigment degradation under high salinity. In contrast, electrical conductivity (EC) values increased in parallel with the rising NaCl concentrations; while EC ranged from 0.17 to 0.43 dS m^{-1} under control treatments, it reached 10–11 dS m^{-1} at 500 mM. This increase indicates the accumulation of salt ions in the growing medium and reflects the intensity of ionic stress in the root zone (Figure 4).

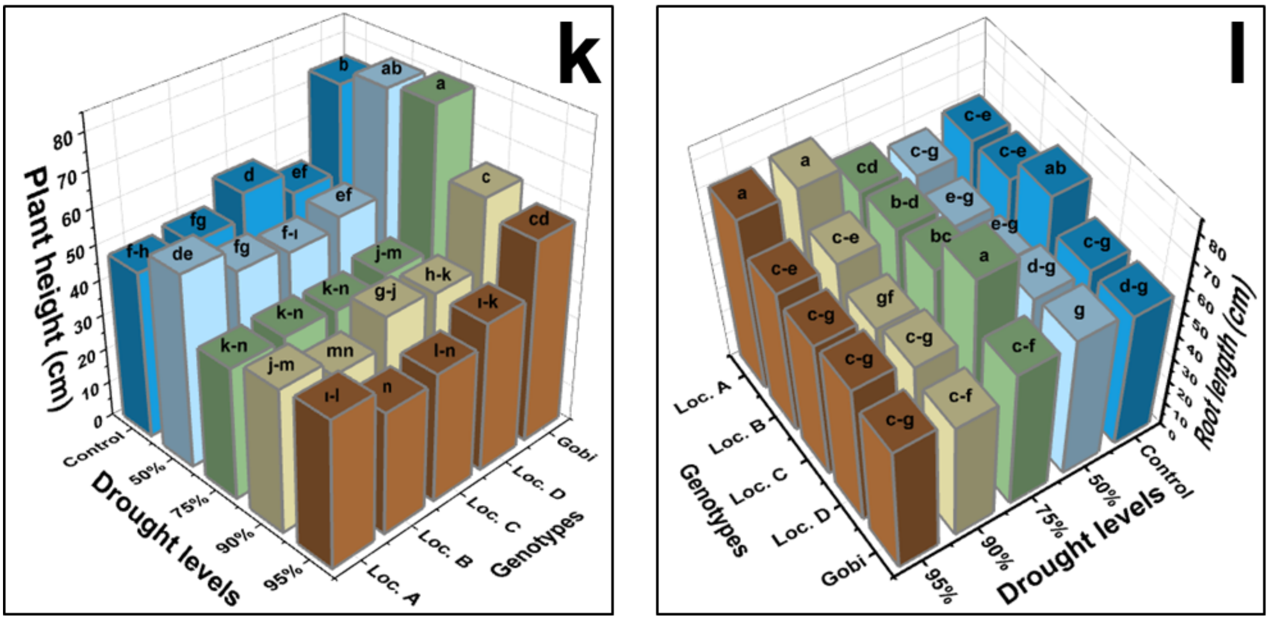

Figure 5. Effects of different drought levels on plant height (k) and root length (l) of *C. dactylon* genotypes.

Morphological Responses to Drought Stress – Increasing levels of water deficit resulted in marked reductions in plant height, number of tillers, and both root and shoot biomass. Under control conditions, plant height ranged from 47.67 to 74.43 cm, whereas under 95% water deficit, it declined to 34.33–57.2 cm. The Gobi genotype maintained the greatest plant height across all treatments (78.97 cm under 50% water deficit), indicating a superior morphological adaptation to drought stress. In terms of root length, genotypes from Locations A and D reached values exceeding 70 cm under severe stress conditions (particularly at 90–95% water deficit), reflecting a deep-rooting strategy to access water. In contrast, the Gobi genotype exhibited greater fluctuations in root length (ranging from 50 to 59 cm) and remained below the location genotypes for this parameter.

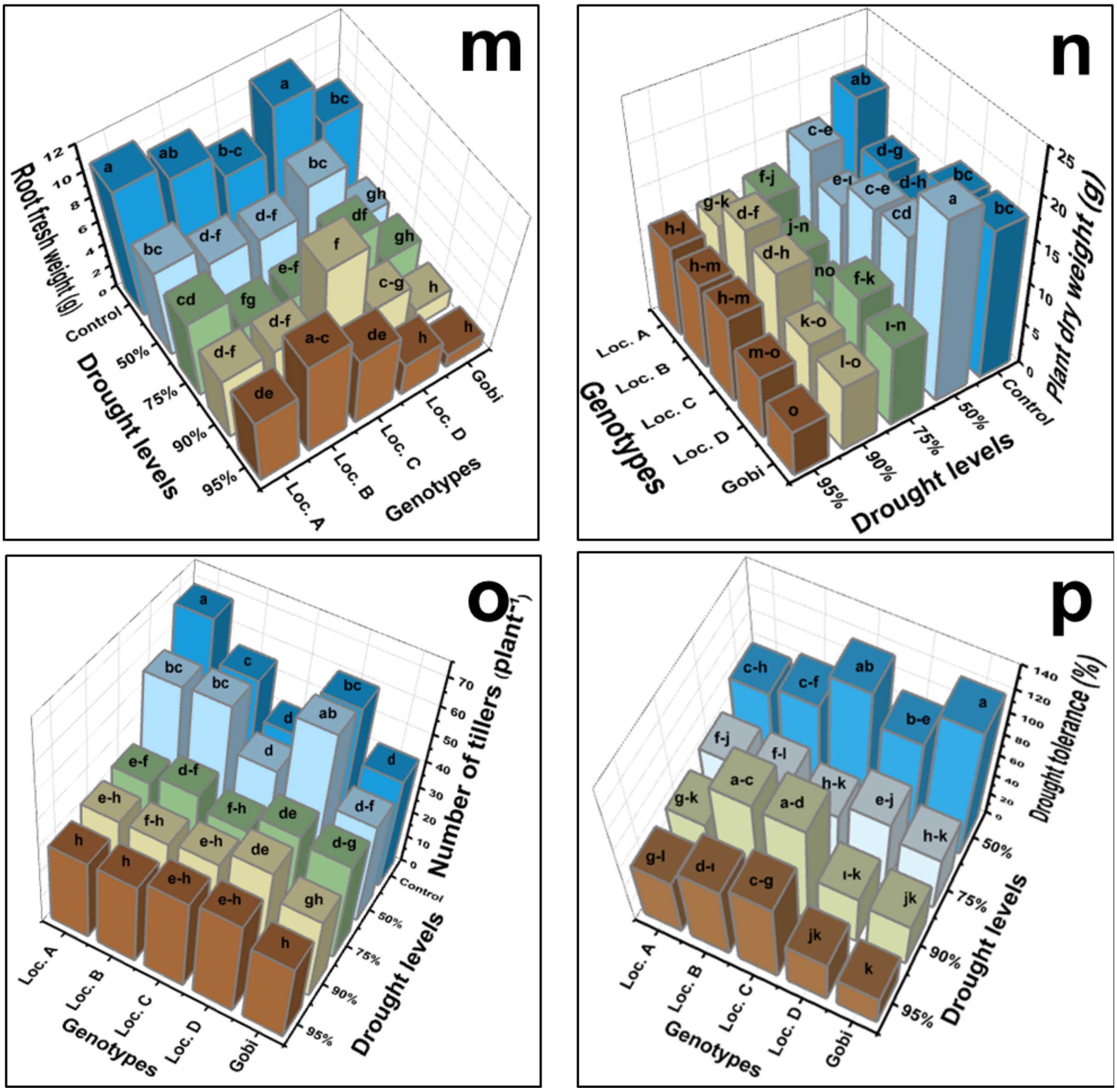

Figure 6. Effects of different drought levels on root and shoot dry weights (m, n), number of branches (o), and drought tolerance (%) (p) of *C. dactylon* genotypes.

Root and shoot dry weights decreased in parallel with increasing drought severity, with the most pronounced reductions observed at 90% and 95% water deficit levels. Under control conditions, root fresh weight ranged from 7.8 to 10.93 g, while at 95% deficit it declined to 1.27–9.03 g. The Gobi genotype exhibited the lowest root weight values under stress. A similar trend was observed for shoot dry weight, which decreased from 13.23–19.27 g under control conditions to 5.53–10.83 g under 95% deficit. The number of tillers was identified as a drought-sensitive parameter, showing approximately a

50% reduction at 95% water deficit across all genotypes. While values ranged between 42 and 69 tillers per plant under control conditions, they declined to 28–34 tillers per plant at the highest stress level. In terms of drought tolerance (%), the Gobi genotype displayed the highest value (121.23%) under moderate stress (50% deficit), but its tolerance dropped sharply to 31.47% under severe conditions (95% deficit). The C location genotype also showed strong adaptation at moderate stress, with a tolerance value of 117.13% at 50% deficit. Overall, both the Gobi and C location genotypes exhibited resilience under moderate water stress but showed sensitivity under severe drought conditions.

4. Discussion

In the present study, as salt concentration increased to 300 mM, the germination rate gradually decreased; however, at 400 and 500 mM NaCl, all seeds (100%) were non-viable. The inhibition or reduction of germination under saline conditions is a common and expected response (Yaşar et al., 2007). Salinity impedes water uptake by seeds, causing osmotic stress, and disturbs plant physiological processes through ion imbalances. Each plant species and genotype exhibits a distinct level of tolerance to salinity. Her plant species and genotype exhibit distinct salinity tolerance thresholds. In previous studies, Tromble (1963) reported germination of C. dactylon at 180 mM, and Al-Humaid (2002) observed it at 150 mM. Our findings demonstrate that germination can continue at higher levels, although it is severely suppressed beyond 300 mM.

Salt stress induces osmotic stress due to low water potential in the root zone, ionic stress from Na^+ and Cl^- accumulation, and nutritional stress caused by imbalances in nutrient uptake (Läuchli, 1986). Salt restricts water absorption by roots, inhibits root growth, and consequently impairs overall plant development. This also disrupts vital physiological processes such as transpiration and respiration (Kanber et al., 1992; Ekmekçi et al., 2005; Çakici and Güneş, 2018). Numerous studies have demonstrated that salt stress reduces root and shoot length and dry biomass (Pessarakli et al., 2008; Çakici and Güneş, 2018). Hu et al. (2012) reported that under salt stress, *C. dactylon* exhibited reductions in shoot height and biomass, while more tolerant genotypes showed increases in root number, root length, and root/shoot ratio. Similarly, Sarıca (2014) found that salinity generally reduced turfgrass growth and quality, although root development was comparatively less affected. Hameed and Ashraf (2008) also observed a significant increase in root weight, accompanied by only minor reductions in shoot dry weight. Such variations may result from genetic diversity and environmental factors.

Salt stress has also been reported to reduce chlorophyll content and cause damage to the photosynthetic apparatus (Hameed and Ashraf, 2008; Yu et al., 2015). Increasing soil salinity interferes with the uptake of essential nutrients such as Na^+, Cl^-, K^+, Ca^{2+}, Mg^{2+}, NO_3^-, and SO_4^{2-} (Devlet, 2024). The detrimental effects of salinity on shoot and root length were similarly emphasized by Pessarakli and Touchane (2006). Accumulation of salts in plant tissues leads to reduced enzymatic activity, cellular dehydration, leaf abscission, and impairment of photosystem function (Munns, 2005; Devlet, 2024). Considerable genotypic variation in salt tolerance has been reported. For example, Dudeck et al. (1983) examined eight bermudagrass cultivars and identified 'Tifdwarf' and 'Tifgreen' as the most tolerant, whereas 'Common' and 'Ormond' were more sensitive. Other studies have also confirmed that *C. dactylon* is generally salt-tolerant (Richards, 1954; Marcum and Murdoch, 1994; Peacock et al., 2004; Hameed and Ashraf, 2008). The species has been shown to survive at high electrical conductivity levels, up to 10.9 dS m^{-1}, further supporting its salt tolerance. Tang et al. (2024) also noted that bermudagrass can withstand pH levels up to 9.3 and exhibits variable germination responses under different salt and alkali stresses.

Under drought stress, *C. dactylon* genotypes displayed diverse responses. Increasing drought severity reduced plant height, root length, tiller number, and chlorophyll content (Husmoen et al., 2012; Lingshuang et al., 2020; Noor et al., 2024). Drought tolerance varied among genotypes; for instance, C and B genotypes exhibited high tolerance (>80%), whereas the Gobi genotype showed a rapid decline in tolerance as drought intensified. Additionally, the interaction between location and drought level influenced tolerance (Beard et al., 1992; Bijanzadeh et al., 2013; Zhou et al., 2013; Mutlu, 2020). Previous studies have shown that bermudagrass genotypes exhibit drought resistance by limiting water loss and have strong potential for water-use efficiency.

Conclusion

The results of this study demonstrate that salinity and drought stresses exert strong inhibitory effects on the germination and early growth of *C. dactylon*. Salinity stress was found to be more detrimental than drought, completely suppressing germination at 300 mM NaCl or higher. Drought stress, on the other hand, caused a gradual reduction in growth parameters, especially under severe water deficit (≥90%). Significant variation among genotypes indicated that tolerance is genetically controlled. The Gobi genotype showed outstanding tolerance to both salinity and drought, followed by the D genotype, while the A genotype was the most sensitive. These outcomes suggest that Gobi can serve as a promising genetic source for developing stress-tolerant cultivars and for establishing sustainable pastures or green areas in arid and saline regions such as the Iğdır Plain. Furthermore, the study emphasizes the importance of genotype selection in enhancing plant resilience under environmental stress conditions.

Ethical Statement

This study does not require ethical approval as it does not involve human participants or experimental animals.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Artificial Intelligence Declaration

The authors declare that no generative artificial intelligence tools were used at any stage of the preparation of this manuscript, including the writing, editing, or refinement of the text, or the creation of any images, figures, graphics, tables, or related titles.

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Author Contributions

Recep Akış: Conceptualization, methodology, experimental design, data collection, data analysis, interpretation of results, and manuscript writing. Bilal Keskin: Supervision, validation, critical revision of the manuscript, and final approval.

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