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Evaluation of Seaweed Application on Physiological Traits of Durum Wheat Landraces Under Drought Stress

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Abstract

Drought stress is one of the major abiotic factors limiting wheat production worldwide and causes significant reductions in plant growth and physiological performance. Seaweed-based biostimulants have recently attracted considerable attention due to their potential role in improving plant tolerance against environmental stresses. This study was conducted to evaluate the effects of seaweed application on morphological and physiological traits of durum wheat landraces exposed to severe drought stress under greenhouse conditions. Two cultivars and eight landraces were used as plant material. Plants were grown under controlled greenhouse conditions, and severe drought stress was initiated at the tillering stage by reducing soil moisture to 20% of field capacity. A 2% seaweed extract was applied twice as a foliar treatment during plant development. Morphological (plant height, tillering number, flag leaf area) and physiological (relative water content) parameters were evaluated. The results demonstrated significant differences among treatments for all investigated traits. While drought stress generally restricted plant growth, seaweed application partially alleviated these negative effects. Specifically, seaweed treatment significantly increased plant height, improved relative water content, and promoted both leaf expansion and tillering across most genotypes, although the magnitude of these responses varied according to the genotype. Overall, the findings indicate that durum wheat landraces possess considerable variability in adaptation to drought stress and that seaweed-based applications may effectively contribute to stress mitigation. This study provides useful information for future breeding programs aiming to improve drought tolerance in durum wheat and highlights the potential of biostimulant applications under water-limited conditions.

Keywords: *Stress tolerance, Biostimulant, Greenhouse experiment, Biomass accumulation, Water deficit*

Introduction

Originating from the Fertile Crescent in the Middle East and domesticated over 10,000 years ago, wheat is among the oldest and most important cultivated crops worldwide (Erenstein et al., 2022). Since its domestication, wheat has remained a cornerstone of global food security, playing a vital role in human nutrition and agricultural systems worldwide (Sharma et al., 2019; Shewry & Hey, 2015). The fact that wheat contains numerous beneficial constituents, including proteins, dietary fiber, vitamins, and phytochemicals, and supplies approximately 20% of the dietary calories consumed by humans, makes it an effective crop against the threat of hunger brought by rapid population growth in the world (Ali et al., 2022; Vafa et al., 2021). Wheat, along with sugar cane, corn, and rice, accounts for almost half of the world's major crop production (FAOSTAT, 2023). More than two-thirds of the wheat produced worldwide is used for food, 20% for forage, and 3-5% for seeds, industrial use, and other uses (Yılmaz & Tomar, 2022). Durum wheat (*Triticum turgidum* L. var. *durum*) is a valuable wheat species that contributes notably to food production sector and agricultural gain, although it constitutes smaller than 7% of the total amount of wheat produced globally. It is a major cereal crop valued for its suitability in the manufacture of semolina-based products, particularly pasta and couscous (Zingale et al., 2023). Canada, Italy, Algeria, Turkiye, USA, Mexico, Kazakhstan, Russia, India, and Azerbaijan are the main durum wheat producers in the world (Martínez-Moreno et al., 2022). However, wheat productivity is increasingly threatened by climate change-induced drought stress. Drought is a major threat to agricultural production and food security globally, as the biggest abiotic stress element resulting in reduced crop yields (Mohammadi et al., 2015). Abiotic stresses like drought provoke significant crop losses, which could lead to a 50% decrease in crop yields (Deolu-Ajayi et al., 2022). Drought adversely affects plant growth, photosynthetic performance, membrane integrity, defense systems, osmotic regulation, pigment content, and cellular architecture (Haghpanah et al., 2024). These alterations are often accompanied by excessive production of reactive oxygen species (ROS), leading to oxidative stress and the activation of complex molecular, biochemical, and physiological responses (Samanta et al., 2024). Tolerance to these abiotic stresses is a key objective in wheat breeding programs. It is necessary to diminish the devastating abiotic stress effects on crops meanwhile enhancing productivity of crop under these abiotic stress situations (Erenstein et al., 2022).

Wheat landraces represent valuable genetic resources owing to their long-term adaptation to local environmental conditions and their potential to harbor stress-resilient traits. To enhance these landraces, breeding

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programs have been established in Europe and Asia over the previous 200 years (Balfourier et al., 2019). Many modern wheat cultivars exhibit a relatively narrow genetic base due to intensive breeding and selection practices. Landraces generally have a wider range of genetic base and have specific adaptations to several environmental conditions from which they originate (Ahmadizadeh et al., 2012; Lopes et al., 2015). Durum wheat landraces, characterized by tall plant architecture, long coleoptiles, and early vigor, likely possess adaptive traits that enable them to survive, thrive, and adapt to drought-prone Mediterranean environments (Jaradat, 2014). Studies show that raised biomass and the thousand grain weight, which are important characteristics in adapting to drought and heat, can be found in the genetic resources of landraces (Lopes et al., 2015). Landraces, therefore, may be a good genetic source of valuable characteristics to be used in wheat breeding studies. Seaweeds, an integral component of marine coastal ecosystems, have long been utilized in agriculture as a source of organic matter and natural fertilizers (Khan et al., 2009).

More recently, seaweed-derived extracts and nutritional supplements have gained considerable attention as sustainable alternatives to synthetic agrochemicals owing to their non-toxic, non-polluting, and readily biodegradable nature (Layek et al., 2019; Rathore et al., 2009; Rabhi et al., 2025). Their use contributes to reduced chemical inputs, improved soil health, and enhanced resource-use efficiency in crop production systems. The beneficial effects of seaweed extracts are primarily attributed to their rich composition of bioactive compounds, including macronutrients, micronutrients, phytohormones, amino acids, proteins, lipids, vitamins, carbohydrates, sterols, and polyphenols (Khan et al., 2009; Szczepanek et al., 2018; Deolu-Ajayi et al., 2022). These compounds promote seed germination, stimulate root and shoot development, enhance nutrient uptake, improve antioxidant capacity, and support overall plant growth and productivity (Rathore et al., 2009). In addition to their growth-promoting properties, numerous studies have demonstrated that seaweed-based biostimulants enhance plant tolerance to drought stress through the regulation of physiological and biochemical processes (Mughunth et al., 2024; Bint Tariq & Umer, 2025).

Consequently, seaweed extract application has been associated with significant improvements in growth and yield across a wide range of crops, including wheat (Szczepanek et al., 2018), soybean (Rathore et al., 2009), rice (Layek et al., 2018), maize (Layek et al., 2019), sorghum (Dalwale et al., 2022), oat (Drygaś et al., 2021), barley (Featonby-Smith & Van Staden, 1987), quinoa (Mohamadpoor et al., 2022), and millet (Rathinapriya et al., 2020). To date, however, studies investigating the interaction between seaweed-based biostimulants and drought tolerance mechanisms in wheat landraces remain scarce. Because genotype-dependent responses to biostimulants have frequently been reported, evaluating genetically diverse germplasm may facilitate the identification of responsive genotypes and improve the efficiency of breeding programs.

Therefore, the present study aimed to evaluate the effect of foliar-applied seaweed extract on the physiological and morphological responses of durum wheat cultivars and landraces under drought stress. The study specifically compared drought-stressed plants with and without seaweed application in order to determine whether seaweed treatment could alleviate the adverse effects of water deficit and to identify genotypes exhibiting superior physiological performance under these conditions.

Materials and Methods

Materials

The study was carried out in the research and application greenhouse of the Department of Agricultural Genetic Engineering, Faculty of Agricultural Sciences and Technologies, Niğde Ömer Halisdemir University, as well as in its laboratories. A total of 10 durum wheat genotypes, comprising two cultivars (Kunduru 1144 and Dumlupınar) and eight landraces (TR 53861, TR 46881, TR 81238, TR 54977, TR 54973, TR 53860, TR 35150, TR 81258) were used in this study (Table 1). A commercial seaweed extract (NATURWIN) containing 45% organic matter, 2% alginic acid, 15% water-soluble K_2O, an electrical conductivity (EC) of 40 dS m^{-1}, and a pH of 8.5-10.5 was used in the experiment (Figure 1).

Table 1. The plant materials used in this study

Genotype	*Name*
1	Kunduru 1144
2	Dumlupınar
3	TR 53861
4	TR 46881
5	TR 81238
6	TR 54977
7	TR 54973
8	TR 53860
9	TR 35150
10	TR 81258

Figure 1. NATURWIN Branded seaweed material

Methods

The experiment consisted of ten genotypes, two treatments (drought and drought + seaweed). Seeds were sown in plastic pots filled with a peat and perlite mixture (3:1, v/v), with ten seeds per pot. The experiment was arranged in a factorial design with three replications. Following seedling emergence, plants were thinned to five uniform seedlings per pot. All pots were maintained at field capacity until the tillering stage to ensure uniform plant establishment.

Field capacity of the potting substrate was determined gravimetrically by saturating the pots with water and allowing free drainage for 24 h. Drought stress was initiated at the tillering stage (45 days after sowing; Zadoks growth stage 25) by reducing soil moisture to 20% of field capacity, and this moisture level was maintained until the end of the experiment (Zadoks et al., 1974). The irrigation volume required to maintain this moisture level was approximately 100 mL pot^{-1}.

Seaweed extract was applied as a 2% foliar spray at the onset of drought stress (Zadoks GS25) and reapplied once at the jointing stage (125 days after sowing; Zadoks GS31) (Zadoks et al., 1974). The selected concentration was based on the recommendation of Ali et al. (2022), who reported superior performance of wheat plants at this concentration. Urea fertilizer (46% N) was supplied to all pots at a rate of 1 g pot^{-1} during the growing period.

Physiological and Morphological Measurements

Plant height (cm) was measured from the soil surface to the tip of the spike at physiological maturity. Fresh leaf weight (FW) was determined immediately after sampling the uppermost fully expanded leaf. The samples were subsequently immersed in distilled water for four hours to obtain turgid weight (TW), followed by oven drying at 70°C for 48 h to determine dry weight (DW). Relative water content (RWC) was calculated according to Barrs and Weatherley (1962) using the following equation: (1)

$$\mathrm{RWC}\ (\%) = [(\mathrm{FW} - \mathrm{DW}) / (\mathrm{TW} - \mathrm{DW})] \times 100) \quad (1)$$

Flag leaf area (FLA, cm²) was calculated by multiplying flag leaf length and maximum leaf width by a correction factor of 0.74 according to the method described by Muller (1991). Tillering number was determined by counting productive tillers per plant at the end of the experimental period. Fresh leaf weight and dry leaf weight were recorded following standard physiological measurement procedures.

Statistical Analysis

The experiment was conducted as a factorial arrangement consisting of genotype and treatment factors with three replications. Analysis of variance (ANOVA) was performed using Statistix 8.1 software to determine the effects of genotype, treatment, and their interaction. Mean comparisons were carried out using the Least Significant Difference (LSD) test at the 5% probability level.

Results

The results of the analysis of variance are presented in Table 2, while the mean comparisons for each trait are illustrated in Figures 2-5.

The analysis of variance revealed significant treatment effects for all investigated traits, whereas genotype effects varied depending on the measured parameter (Table 2). Treatment significantly affected tillering number ($P < 0.01$), flag leaf area ($P < 0.01$), and relative water content ($P < 0.01$). Genotype significantly influenced tillering number ($P < 0.01$), whereas its effects on flag leaf area and relative water content were not significant. A significant genotype × treatment interaction was detected only for flag leaf area ($P < 0.05$), indicating differential responses of genotypes to seaweed application under drought conditions. In contrast, genotype × treatment interactions for tillering number and relative water content were not significant.

Table 2. Analysis of Variance Table for Plant Height, Tillering Number, Flag Leaf Area, and Relative Water Content (RWC)

Trait	*Source of variation*	*Mean square*	*F*	*P*
Plant Height	Genotypes	215.44	4.82	0.0012**
	Treatment	3154.20	185.34	0.0001**
	Interaction (G×T)	42.15	0.88	0.5482 ^{ns}
Tillering Number	Genotypes	1.6164	4.26	0.0027**
	Treatment	2.3892	132.73	0.0075**
	Interaction (G×T)	0.2943	0.66	0.7375 ^{ns}
Flag Leaf Area	Genotypes	15.566	1.59	0.1712 ^{ns}
	Treatment	337.224	196.77	0.0050**
	Interaction (G×T)	27.056	2.77	0.0212*
RWC	Genotypes	1213.68	1.05	0.4303 ^{ns}
	Treatment	1172.56	769.72	0.0013**
	Interaction (G×T)	2009.64	1.74	0.1336 ^{ns}

ns: not significant; * P < 0.05; ** P < 0.01.

Plant Height

Analysis of variance revealed that both genotype and treatment significantly affected plant height under drought conditions (Table 2). However, the genotype × treatment interaction was not significant ($P > 0.05$), indicating that the response to seaweed application was generally consistent among the evaluated genotypes.

Mean comparisons showed that plant height was higher in the drought + seaweed treatment than in the drought treatment for all evaluated genotypes (Figure 2). Plant height under drought + seaweed treatment ranged from 62.00 cm (TR 81238) to 91.00 cm (TR 53860), whereas values under drought treatment ranged from 54.50 cm (Dumlupınar) to 78.00 cm (TR 53860). The greatest increase associated with seaweed application was observed in TR 35150, where plant height increased from 63.50 cm under drought to 81.67 cm following seaweed application. Similarly, substantial improvements were recorded in Dumlupınar (54.50-71.50 cm) and Kunduru 1144 (63.33-76.00 cm). In contrast, the smallest differences between treatments were observed in TR 46881, TR 81238, and TR 54973. Overall, seaweed application promoted plant height in all durum wheat genotypes evaluated under drought stress, although the magnitude of the response varied among genotypes.

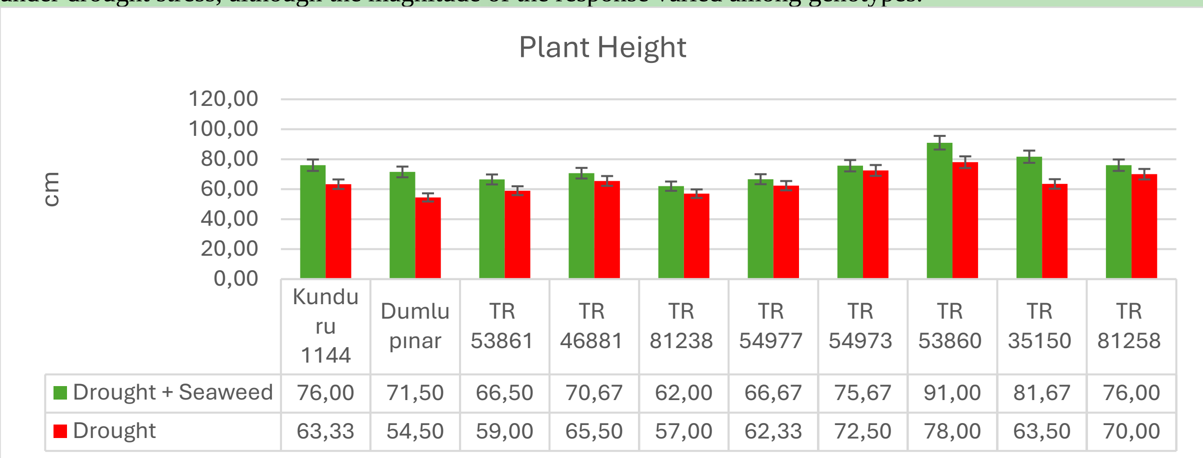
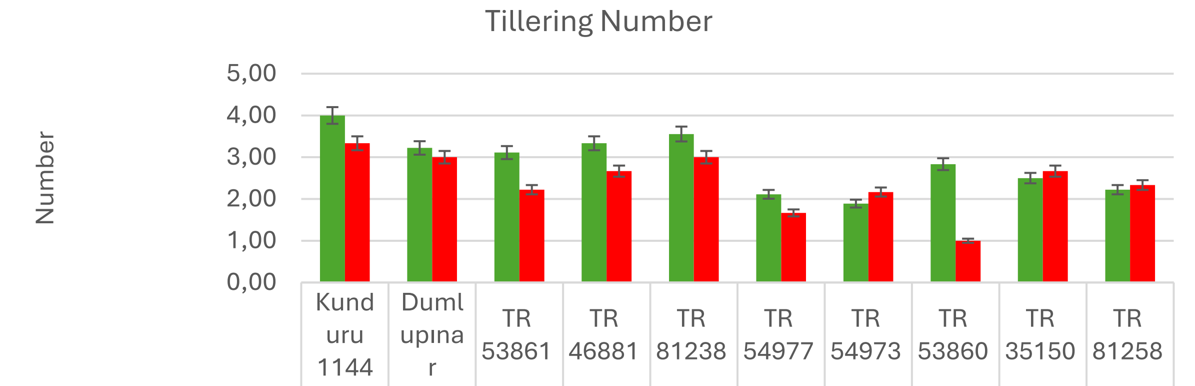


Figure 2. Plant height of durum wheat genotypes under drought + seaweed and drought groups

Tillering Number

Seaweed application generally increased tillering number under drought conditions in most durum wheat genotypes (Figure 3). The highest tillering number under drought + seaweed treatment was recorded in Kunduru 1144 (4.00 tillers plant^{-1}), followed by TR 81238 (3.56 tillers plant^{-1}) and TR 46881 (3.33 tillers plant^{-1}). Under drought treatment alone, Kunduru 1144 also exhibited the highest value (3.33 tillers plant^{-1}), whereas TR 53860 showed the lowest tillering number (1.00 tillers plant^{-1}). Although the magnitude of response differed among genotypes, seaweed application increased tillering number in the majority of the evaluated genotypes.

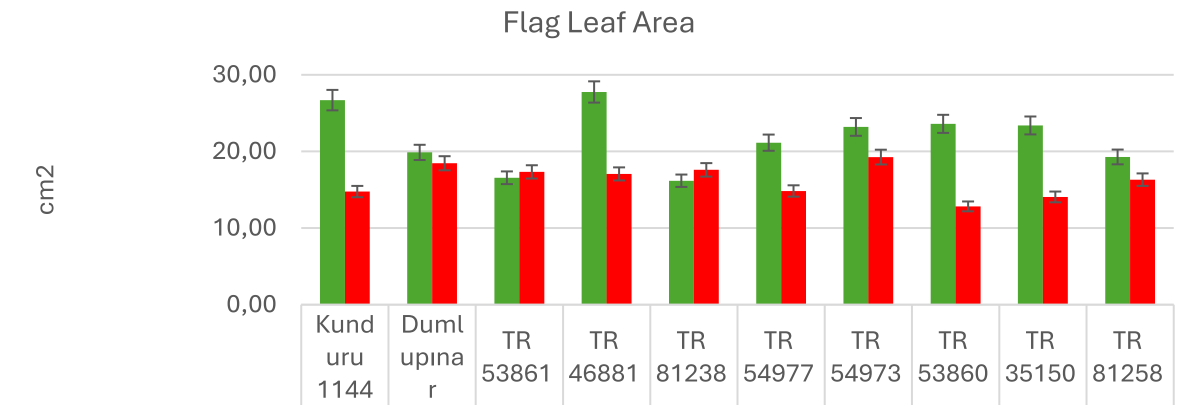


	Kunduru 1144	Dumlupınar	TR 53861	TR 46881	TR 81238	TR 54977	TR 54973	TR 53860	TR 35150	TR 81258
Drought + Seaweed	4,00	3,22	3,11	3,33	3,56	2,11	1,89	2,83	2,50	2,22
Drought	3,33	3,00	2,22	2,67	3,00	1,67	2,17	1,00	2,67	2,33

Figure 3. Tillering numbers of durum wheat genotypes under drought + seaweed and drought groups

Flag Leaf Area

Flag leaf area differed significantly between drought and drought + seaweed treatments (Figure 4). Seaweed-treated plants generally exhibited larger flag leaf areas than drought-treated plants. The highest flag leaf area under seaweed application was observed in TR 46881 (27.76 cm²), followed by Kunduru 1144 (26.70 cm²). In contrast, the smallest flag leaf area under drought treatment was recorded in TR 53860 (12.83 cm²). Considerable variation in treatment response was observed among genotypes, consistent with the significant genotype × treatment interaction detected by the analysis of variance.



	Kunduru 1144	Dumlupınar	TR 53861	TR 46881	TR 81238	TR 54977	TR 54973	TR 53860	TR 35150	TR 81258
Drought + Seaweed	26,70	19,88	16,57	27,76	16,18	21,14	23,20	23,60	23,39	19,28
Drought	14,76	18,46	17,33	17,07	17,60	14,84	19,26	12,83	14,07	16,32

Figure 4. Flag leaf areas of durum wheat genotypes under drought + seaweed and drought groups

Relative Water Content

Relative water content (RWC) was significantly affected by treatment (Table 2). Under drought + seaweed treatment, RWC values ranged from 55.81% to 84.38%, whereas drought-treated plants ranged from 44.34% to 78.21% (Figure 5). The highest RWC under seaweed application was obtained from TR 54977 (84.38%), while the lowest value was observed in TR 81258 (55.81%). Under drought treatment, TR 54973 exhibited the highest RWC (78.21%), whereas TR 53861 had the lowest value (44.34%). Overall, seaweed application resulted in higher RWC values in most evaluated genotypes under drought conditions.

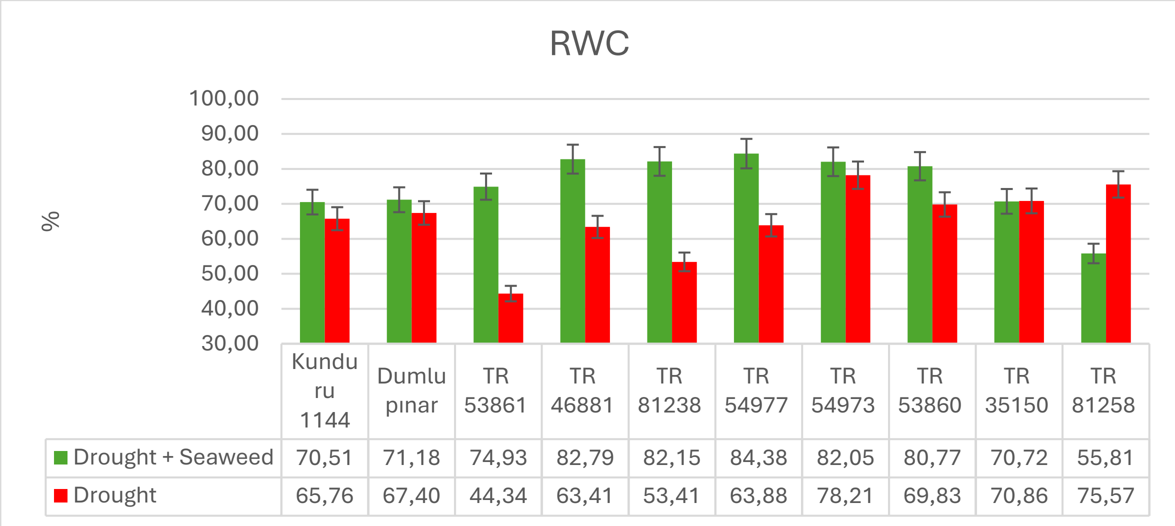


Figure 5. RWC means of durum wheat genotypes under drought + seaweed and drought groups

Discussion

Seaweed applications generally increased plant height compared with drought-stressed plants that did not receive seaweed treatment, indicating that seaweed partially alleviated the inhibitory effects of drought on vegetative growth. Plant height is one of the first morphological traits affected by water deficit because drought limits cell expansion and stem elongation through reduced turgor pressure and photosynthetic activity. The higher plant height observed following seaweed application suggests that the biostimulant helped maintain plant growth despite severe water limitations.

These findings are consistent with those of Ali et al. (2022), who reported that seaweed extract promoted shoot growth and improved drought tolerance in wheat under water-deficit conditions. Similarly, Kasim et al. (2015) demonstrated that seaweed application mitigated drought-induced growth inhibition by improving physiological performance, while Sharma et al. (2019) reported that seaweed extracts enhanced drought tolerance through improved water relations and hormonal regulation. The variation in response among genotypes observed in the present study further indicates that the effectiveness of seaweed application depends on the genetic background of the plant, a conclusion also supported by Deolu-Ajayi et al. (2022).

Relative water content is one of the most reliable physiological indicators of plant water status under drought stress. In the present study, seaweed-treated plants generally maintained higher RWC values than drought-treated plants without seaweed application, indicating an improved ability to retain water under limited soil moisture conditions.

Seaweed extracts contain numerous bioactive compounds, including phytohormones, polysaccharides, amino acids, and osmoprotective substances that contribute to osmotic adjustment and improved cellular hydration under drought stress (Khan et al., 2009; Deolu-Ajayi et al., 2022). Similar increases in RWC following seaweed application have been reported by Ali et al. (2022), who associated this improvement with enhanced drought adaptation in wheat. Likewise, Kasim et al. (2015) demonstrated that seaweed-treated wheat plants maintained better leaf water status than untreated drought-stressed plants. The relatively consistent increase in RWC among the evaluated genotypes suggests that seaweed application positively affected plant water relations regardless of genotype.

Flag leaf area was generally greater in seaweed-treated plants than in drought-stressed plants without seaweed application. Maintenance of flag leaf area under drought is particularly important because the flag leaf contributes substantially to assimilate production during the grain-filling period. Therefore, preserving leaf expansion under stress may help sustain photosynthetic capacity even under reduced water availability.

The present findings agree with those of Kasim et al. (2015), who reported that seaweed extracts reduced the detrimental effects of drought on leaf development in wheat. Similar improvements in vegetative growth have also been reported in several cereal species, including maize (Layek et al., 2019), barley (Featonby-Smith and Van Staden, 1987), and oat (Drygaś et al., 2021). The significant genotype × treatment interaction observed for flag leaf area indicates that the magnitude of improvement varied among genotypes, suggesting differences in their responsiveness to seaweed-derived biostimulants under drought stress.

Seaweed application generally promoted tillering under drought conditions, although the magnitude of improvement differed among the evaluated genotypes. Tillering is an important yield-related trait because productive tillers directly influence spike number and ultimately grain yield. Maintaining tiller formation under drought therefore represents an important component of stress adaptation.

The positive effect observed in the present study may be associated with naturally occurring growth regulators present in seaweed extracts, particularly cytokinins and auxins, which stimulate vegetative growth and tiller development (Khan et al., 2009). Similar beneficial effects of seaweed-based biostimulants on cereal growth have previously been reported in wheat (Szczepanek et al., 2018), barley (Featonby-Smith and Van Staden, 1987), maize (Layek et al., 2019), and sorghum (Dalwale et al., 2022). Although genotypes differed in their tillering capacity, the overall improvement observed following seaweed application suggests that seaweed can partially compensate for the negative effects of drought on vegetative development.

Conclusion

This study evaluated the effects of foliar seaweed application on the physiological and morphological responses of durum wheat cultivars and landraces exposed to severe drought stress under greenhouse conditions. Significant treatment effects were observed for plant height, flag leaf area, relative water content, and tillering number, demonstrating that seaweed application alleviated the adverse effects of drought on plant growth and water status. In general, seaweed-treated plants exhibited greater plant height, larger flag leaf area, higher relative water content, and improved tillering capacity compared with drought-stressed plants without seaweed application.

The responses to seaweed application varied among genotypes, indicating the existence of genetic differences in the utilization of seaweed-derived biostimulants under drought conditions. Nevertheless, the overall improvement observed in most genotypes suggests that seaweed application can contribute to maintaining plant growth and physiological performance under water-limited conditions.

The findings indicate that seaweed-based biostimulants represent a promising management strategy for mitigating drought stress in durum wheat. In addition, the observed variation among landraces highlights their potential as valuable genetic resources for breeding programs aimed at improving drought tolerance. Further studies under field conditions and across different drought intensities are recommended to validate the greenhouse results and optimize application strategies for practical agricultural use.

Declarations

Author Contribution Statement

Buse Tuna: Investigation, greenhouse experiment, data collection, physiological and morphological measurements, formal analysis, and writing – original draft.

İbrahim Köken: Conceptualization, methodology, experimental design, supervision, data validation, formal analysis, writing – review & editing.

Ufuk Demirel: Project administration, supervision, methodology, resources, critical review, and editing of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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