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Changes in Photosynthetic Efficiency, Biomass, and Sugar Content of Sweet Sorghum Under Different Water and Salt Conditions in Arid Region of Northwest China

Weihao Sun [1,2], Zhibin He [1,*], Bing Liu [1], Dengke Ma [1], Rui Si [1], Rui Li [1], Shuai Wang [1,2] and Arash Malekian [3]

[1] China and Iran Joint Laboratory on Agriculture and Ecology in Arid Regions, Linze Inland River Basin Research Station, Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; sunweihao@nieer.ac.cn (W.S.); liubing@lzb.ac.cn (B.L.); dengkema19@163.com (D.M.); sirui@lzb.ac.cn (R.S.); lirui@nieer.ac.cn (R.L.); wangs0504@163.com (S.W.)
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Faculty of Natural Resources, University of Tehran, Karaj 31585-3314, Iran; malekian@ut.ac.ir
* Correspondence: hzbmail@lzb.ac.cn

Abstract: Sweet sorghum (*Sorghum bicolor* L. Moench) has significant cultivation potential in arid and saline–alkaline regions due to its drought and salt tolerance. This study aims to evaluate the mechanisms by which increased soil salinity and reduced irrigation affect the growth, aboveground biomass, and stem sugar content of sweet sorghum. A two-year field experiment was conducted, with four salinity levels (CK: 4.17 dS/m, S1: 5.83 dS/m, S2: 7.50 dS/m, and S3: 9.17 dS/m) and three irrigation levels (W1: 90 mm, W2: 70 mm, and W3: 50 mm). The results showed that increased salinity and reduced irrigation significantly reduced both the emergence rate and aboveground biomass, with the decreases in the emergence rate ranging from 11.0% to 36.2% and the reductions in the aboveground biomass ranging from 15.9% to 43.8%. Additionally, increased soil salinity led to reductions in stem sugar content of 6.3% (S1), 8.8% (S2), and 12.8% (S3), respectively. The results also indicated that photosynthetic efficiency, including the net photosynthetic rate (Pn), stomatal conductance (Gs), and chlorophyll content (SPAD), was significantly hindered under increased water and salt stress, with the Pn decreasing by up to 50.4% and the SPAD values decreasing by up to 36.3% under the highest stress conditions. These findings underscore the adverse impacts of increased soil salinity and reduced irrigation on sweet sorghum's growth, photosynthetic performance, and sugar accumulation, offering critical insights for optimizing its cultivation in arid and saline environments.

Keywords: drought; salt stress; photosynthesis; sugar content; sweet sorghum; arid region

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1. Introduction

The global challenge of water scarcity, worsened by climate change, significantly hampers agricultural productivity [1,2]. In arid areas such as northwest China, where precipitation is low and evaporation rates are high [3], water availability for crop growth is severely limited [4,5]. Concurrently, irrigated farmlands in arid areas are highly prone to salinization, with approximately 20% of irrigated lands showing trends towards salinization [6,7]. The dual threats of water scarcity and soil salinization pose significant obstacles to crop production, endangering food security in these vulnerable areas [8,9]. Therefore, there is an urgent need to promote the cultivation of drought-resistant and salt-tolerant crops, offering a promising solution for sustainable agriculture in arid areas.

Known for its resilience in semi-arid and saline settings, sweet sorghum (*Sorghum bicolor* L. Moench) serves as a critical crop for bioenergy and livestock feed in areas struggling with water shortages and soil salinization [10–12]. Its adaptability to harsh conditions, high biomass yield, and substantial sugar content make sweet sorghum an attractive

candidate for cultivation in arid and semi-arid areas worldwide [13]. However, these environmental stresses significantly impact sweet sorghum's growth, photosynthetic efficiency, biomass accumulation, and sugar content, which are critical factors for its economic viability and productivity.

The primary environmental constraints on sweet sorghum productivity are water deficits and soil salinity. Water stress, characterized by insufficient water availability, can lead to reduced plant height, stem diameter, and biomass due to impaired nutrient uptake and photosynthetic efficiency [14,15]. Similarly, salt stress, caused by high soil salinity, negatively affects plant growth by inducing osmotic stress, ion toxicity, and nutrient imbalance, ultimately reducing both biomass and sugar accumulation [16,17]. Existing research has highlighted its ability to grow in harsh conditions and its potential as a biofuel source, feedstock, and sugar crop [10,11,18]. However, there is a limited understanding of how sweet sorghum accumulates sugar under different water and salt stress conditions and how these stresses affect photosynthetic efficiency. This knowledge gap is crucial because photosynthesis directly influences both biomass and sugar content, thereby determining the crop's value for bioenergy production and nutritional purposes. Understanding the mechanisms that affect photosynthetic efficiency and sugar accumulation under stress conditions can significantly enhance the efficiency of sweet sorghum cultivation, particularly in arid and saline regions where these stresses are prevalent.

In this study, we conducted a two-year field experiment in a typical oasis in the arid region in Northwest China to evaluate the effects of water and salt stress on the growth, photosynthetic efficiency, biomass, and sugar content of sweet sorghum. Our specific objectives were to assess how different levels of water and salt stress influence the physiological and growth responses of sweet sorghum, particularly its photosynthetic characteristics, biomass, and sugar content. By addressing the critical gap in understanding the relationship between photosynthetic performance, sugar accumulation, and environmental stresses, this research aims to support sustainable agricultural practices and enhance the utility of sweet sorghum for bioenergy production and nutritional purposes.

2. Materials and Methods

2.1. Study Area

The experiments took place at the Linze Inland River Basin Research Station, which is affiliated with the Chinese Academy of Sciences (39°21′ N, 100°02′ E, altitude 1400 m), from April to September 2021 and April to September 2022. This region has a typical temperate continental climate with an average annual temperature of 7.6 °C and an annual precipitation of 117 mm. Significant evaporation occurs during the summer months when temperatures can exceed 30 °C. The annual evaporation is 2390 mm, and the frost-free period is about 165 days. The main soil type in the study area was characterized as sandy, belonging to the Aridisols soil order [19], with an average soil bulk density of 1.42 g cm^{-3}, field capacity of 23.2%, and groundwater depth ranging from 3 to 8 m. The soil in the study area had an electrical conductivity (EC) ranging from 0.6 to 9.7 dS/m and a pH value between 7.51 and 9.31. The temperature and precipitation data for 2021 and 2022 are shown in Figure 1.

2.2. Experimental Design

The sweet sorghum variety used in this experiment was "Jintian No. 1", an early-maturing variety developed by the Institute of Modern Physics, Chinese Academy of Sciences. Planting was carried out on 15 April 2021 and 20 April 2022, with harvesting on 25 September 2021 and 30 September 2022. The experiment was conducted in a random field plot. The plot was constructed using linoleum, polyethylene film, and brick in a 16 m^2 (4 m × 4 m) anti-seepage bottomless pool with a side wall depth of 1.5 m. According to the local farmland management practices, plastic film was laid in the plot, the row spacing of sweet sorghum was 40 cm, and the plant spacing was 20 cm, with a planting density of 10,050 plants per hectare.

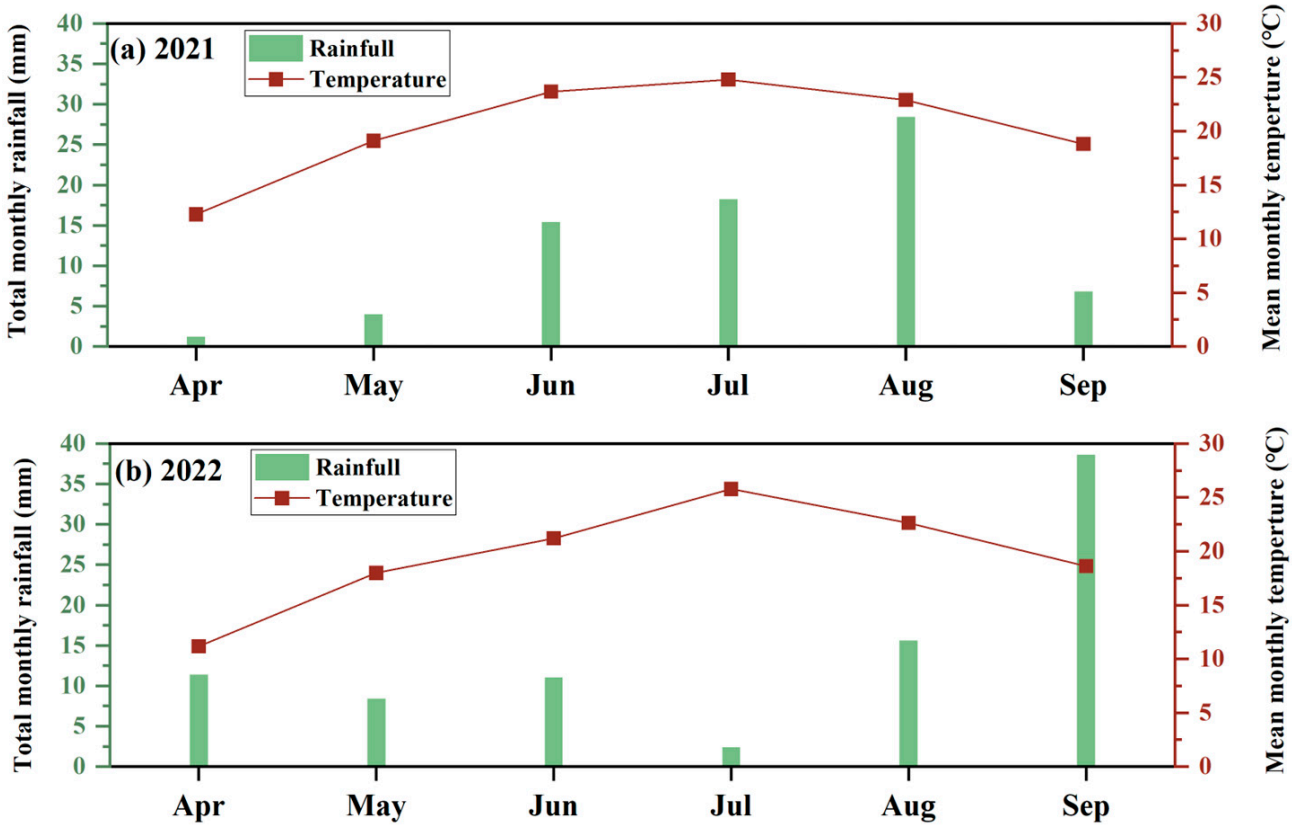


Figure 1. The total monthly rainfalls and mean monthly temperatures during the experiment.

The experiment was a two-factor split-plot design, where the main zone was treated with salt stress and the split zone was treated with water stress. Salt stress level refers to the selection of undisturbed soil with different EC gradients in farmlands in the experimental collection area, and salt stress treatment was carried out based on soil EC values. Specific experimental settings are as follows: CK (EC = 4.17 dS/m): from the soil with low salinity in the test area; S1 (EC = 5.83 dS/m): soil from the test area with moderate salinity; S2 (EC = 7.50 dS/m): from the soil with high salinity in the test area; S3 (EC = 9.17 dS/m): soil from the test area with the highest salinity. Water stress was induced with three levels of irrigation quotas, including W1 (90 mm), W2 (70 mm), and W3 (50 mm). For the W1 treatment, the irrigation lower limit was set at 60% of the field capacity (calculated based on soil moisture content from the 0 to 150 cm soil depth). The irrigation quota for W1 is 90 mm per irrigation event. For the W2 and W3 treatments, the irrigation timing was synchronized with W1, meaning that when W1 required irrigation, both W2 and W3 also received irrigation at the same time. However, the irrigation quotas for W2 and W3 were different: W2 received 70 mm, and W3 received 50 mm per irrigation event. Each treatment combination was replicated three times, resulting in a total of 36 experimental plots. The stress conditions were applied continuously throughout the entire growing season, starting from the seedling stage until harvest.

Before seeding, 140 kg ha^{-1} of nitrogen fertilizer (46% urea nitrogen) and 70 kg ha^{-1} of phosphate fertilizer (superphosphate, with available phosphorus content above 12%) were applied as a base fertilizer. Nitrogen fertilizer (170 kg ha^{-1}) and phosphate fertilizer (70 kg ha^{-1}) were applied at jointing stage. At the flowering stage, 30 kg ha^{-1} nitrogen fertilizer was applied [20]. Irrigation was carried out by monitoring soil moisture content during the growth period. Water stress was monitored using soil moisture sensors installed at various depths (0–150 cm) to track moisture content. During the experiment in 2021 and 2022, 8 irrigation sessions were conducted respectively.

2.3. Measurement Items and Methods

2.3.1. Growth Characteristics

Three representative sweet sorghum plants were selected and tagged in each experimental plot. After the sweet sorghum growing season, plant height, stem diameter, internode number, and blade number per plant were measured, with plant height and stem diameter measured using a tape measure and Vernier calipers, respectively.

2.3.2. Photosynthetic Characteristics

At the half-bloom growth stage, the photosynthetic rates of the leaves from three tagged plants were measured using a Li-6400 portable photosynthesis system (LI-COR, Lincoln, NE, USA), with data collected between 9:00 and 11:00 a.m. on sunny days. The measured parameters included net photosynthetic rate (Pn), stomatal conductance (Gs), and intercellular CO_2 concentration (Ci). Additionally, leaf greenness index was estimated using a SPAD-502 portable chlorophyll meter (Konica Minolta Holdings, Inc., Tokyo, Japan) on the leaves of the three tagged plants.

2.3.3. Biomass

Dry biomass of aboveground plants was used to characterize the biomass of sweet sorghum. During the harvest period, three sweet sorghum plants were randomly selected from each plot for harvesting. The samples were divided into stems, leaves, and panicles, then dried in an oven at 105 °C for 30 min, followed by drying at 85 °C until constant weight was achieved (approximately 12 h), and then weighed to determine dry weight.

2.3.4. Stem Sugar Content

During the harvest period, whole sweet sorghum plants were excavated, and the sugar concentration of the juice from the top, middle, and bottom parts of the stems was measured using a sugar tester (DBR45, Hangzhou Chuanghe Environmental Equipment Co., Ltd., Hangzhou, China). The sum of the mean value of sugar concentration in the top, middle, and bottom stem parts represented the sugar content of the stem juice for that plant.

2.4. Data Processing

Data analysis was conducted using Excel 2019 and SPSS 26. Analysis of variance (ANOVA) and Duncan's multiple range test ($\alpha = 0.05$) were used for variance analysis and multiple comparisons. Using Origin 2021, regression equations for soil EC value, aboveground biomass, and stem sugar content were developed.

3. Results

3.1. Emergence Rate

The emergence rate of sweet sorghum in both 2021 and 2022 was significantly affected by water stress and salt stress ($p < 0.01$), and significant differences were also observed in the interaction of water and salt stresses on the emergence rate of the sweet sorghum ($p < 0.05$) (Table S1). The emergence rate of the sweet sorghum declined progressively with rising salt stress levels under identical water conditions. Compared to W1CK, the emergence rate in W1S3 decreased by 28.0% and 22.45% in 2021 and 2022, respectively. In the W3 treatment, the emergence rate in W3S3 decreased by 41.3% and 45.6% compared to W3CK in 2021 and 2022, respectively. This indicated that the impact of salt stress on sweet sorghum emergence is more pronounced under drought conditions. Additionally, the overall emergence rate in the second year was slightly higher than in the first year (Table 1).

Table 1. Emergence rate of sweet sorghum under different water and salt stress treatments (n = 3).

Year	Irrigation	Salt	Emergence Rate%
2021	W1	CK	97.2 ± 3.5 a
		S1	86.0 ± 3.6 b
		S2	82.4 ± 5.6 b
		S3	70.0 ± 7.04 c
	W2	CK	91.6 ± 7.5 a
		S1	81.6 ± 3.9 a
		S2	61.2 ± 12.0 b
		S3	50.0 ± 8.9 b
	W3	CK	64.0 ± 6.6 a
		S1	46.4 ± 5.9 b
		S2	47.2 ± 8.5 b
		S3	37.6 ± 7.3 b
2022	W1	CK	98.4 ± 0.02 a
		S1	97.2 ± 2.0 a
		S2	94.0 ± 3.6 a
		S3	76.4 ± 7.5 b
	W2	CK	94.8 ± 3.0 a
		S1	83.6 ± 2.3 b
		S2	82.0 ± 2.8 b
		S3	67.6 ± 4.6 c
	W3	CK	72.0 ± 3.8 a
		S1	57.2 ± 6.1 b
		S2	48.8 ± 6.5 b
		S3	39.2 ± 5.9 c

W: Water stress treatment, S: Salt stress treatment. Different letters indicate significant differences between treatments at a level of $\alpha = 0.05$ with Duncan's multiple range test.

3.2. Growth Characteristics

The plant height, stem diameter, and internode number of sweet sorghum in both 2021 and 2022 were significantly affected by water stress and salt stress ($p < 0.01$), while the blade number was only affected by salt stress ($p < 0.05$) (Table S2). Across both years, there was little difference in plant height between W1 and W2, but the plant height in W3 decreased by 10% to 12% compared to W1. Within each water stress treatment, increasing levels of salt stress consistently reduced plant heights. The tallest plants were observed in the W1CK treatment (average 321.7 cm), while the shortest was in the W3S3 treatment (average 221.2 cm) (Figure 2a,b). The stem diameter significantly decreased as the water stress increased. In W1 and W2, the stem diameter also showed a decreasing trend as the salt stress increased. In W3, the stem diameter in W3S3 exhibited the most significant decreases, with a reduction of 17.5% to 20% compared to W3CK (Figure 2c,d). Regarding the internode number, there was little difference between W1 and W2, but W3 had 20% to 22% fewer internodes than W1 across both years. In all water stress treatments, the internode number decreased with increasing salt stress, with the most significant reduction being observed in the S3 treatment (Figure 2e,f). The blade number showed no significant differences between water stress treatments, but W3S3 had approximately 20% fewer blades compared to W1CK (Figure 2g,h).

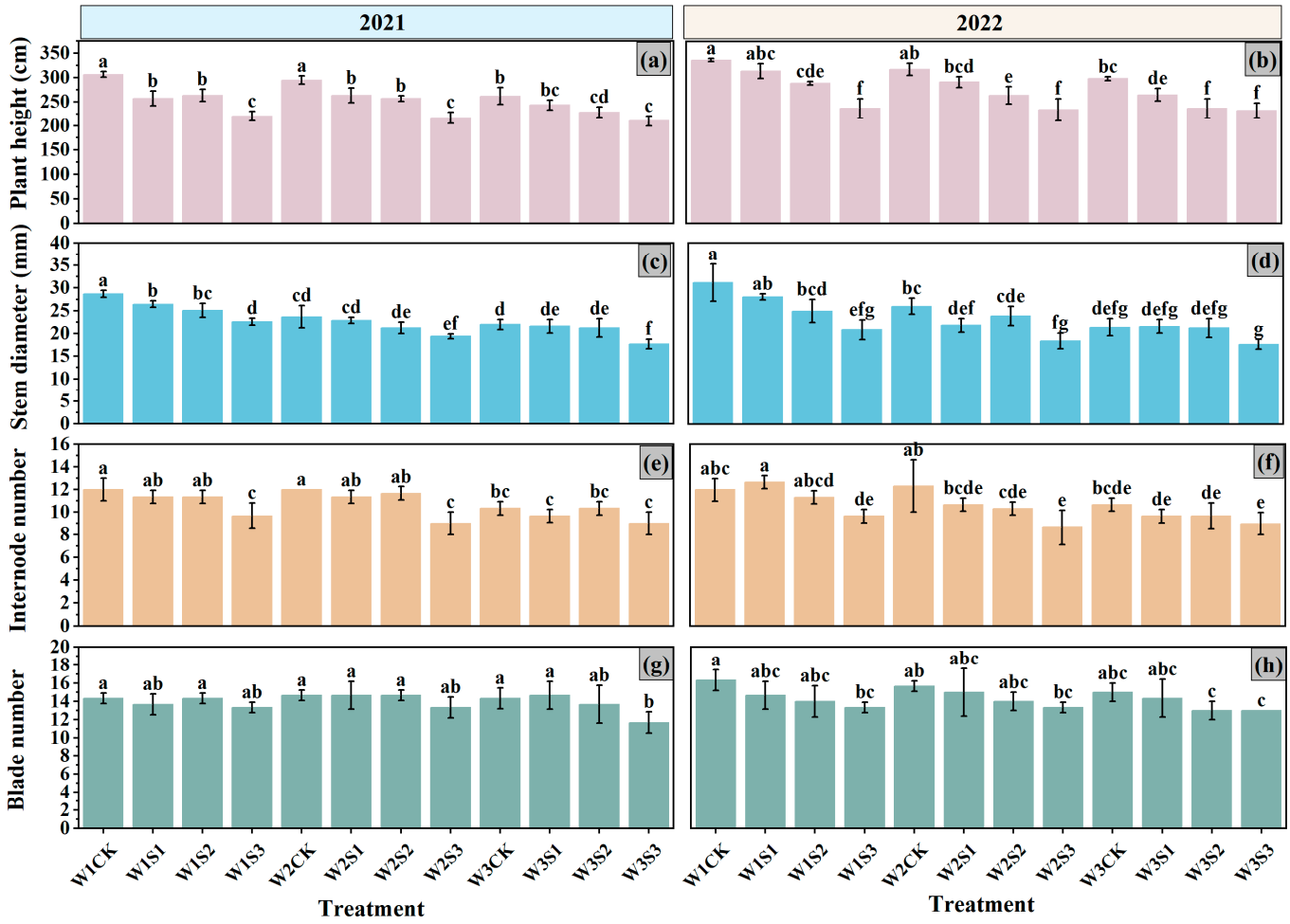


Figure 2. Plant height (**a**,**b**), stem diameter (**c**,**d**), internode number (**e**,**f**) and blade number (**g**,**h**) of sweet sorghum under different water and salt stress treatments in 2021 and 2022 (n = 9). Different letters indicate significant differences between treatments at a level of $\alpha = 0.05$ with Duncan's multiple range test. Error bars represent standard deviation.

3.3. Photosynthetic Characteristics

The Pn, Gs, Ci, and SPAD parameters of the sweet sorghum in both 2021 and 2022 were significantly influenced by water and salt stress ($p < 0.05$) (Table S3). Across both years, the Pn significantly decreased as the water stress and salt stress increased, with the lowest values observed in W3S3. In 2021, the Pn in W3S3 decreased by approximately 44.4% compared to W1CK (Figure 3a), and in 2022, it decreased by around 50.4% (Figure 3b). The Gs also showed a decreasing trend with increased water and salt stress. In 2021, the Gs in W3S3 was reduced by approximately 57.1% compared to W1CK (Figure 3c), and in 2022, it was reduced by around 51.3% (Figure 3d). The Ci increased under increased salt stress, with the highest Ci observed in W3S3. In 2021, the Ci in W3S3 increased by approximately 27.8% compared to W1CK (Figure 3e), and in 2022, it increased by about 28.6% (Figure 3f). The SPAD was also significantly affected by both stress factors, with the SPAD values decreasing as the water and salt stress increased. In 2021, the lowest SPAD value was recorded in the W3S3 treatment, which was approximately 36.3% lower than in W1CK (Figure 3g), and in 2022, it was around 34.7% lower (Figure 3h). These results suggest that increased water and salt stress significantly hinder the photosynthetic efficiency of sweet sorghum.

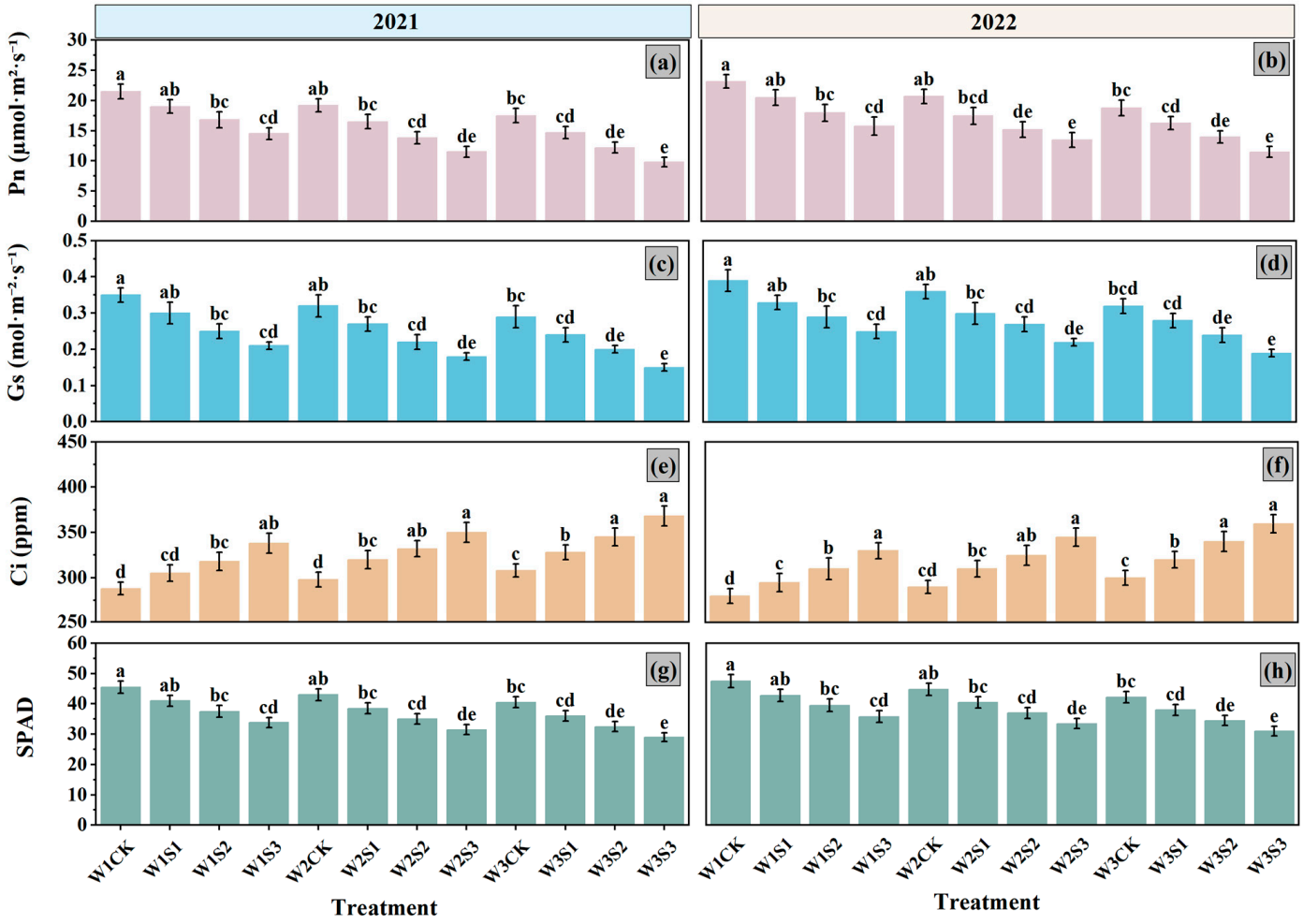


Figure 3. Photosynthetic rate (Pn, (**a**,**b**)), stomatal conductance (Gs, (**c**,**d**)), intercellular CO_2 concentration (Ci, (**e**,**f**)), and chlorophyll content (SPAD, (**g**,**h**)) of sweet sorghum under different water and salt stress treatments in 2021 and 2022 (n = 9). Different letters indicate significant differences between treatments at a level of α = 0.05 with Duncan's multiple range test. Error bars represent standard deviation.

3.4. Aboveground Biomass

The stem, leaf, panicle, and aboveground biomass of the sweet sorghum in both 2021 and 2022 were significantly affected by water stress and salt stress ($p < 0.01$), while the interaction between water and salt stresses had a significant effect only on the panicle biomass, but not on the stem or leaf (Table S4). Overall, the aboveground biomass decreased with increasing water and salt stress. Specifically, the biomass decreased across irrigation treatments in the order of W1 > W2 > W3 and across salt stress levels in the order of CK > S1 > S2 > S3. Compared to W1, the aboveground biomass of the sweet sorghum decreased by 20.4% and 43.8% for W2 and W3, respectively. Similarly, compared to CK, the aboveground biomass of the sweet sorghum decreased by 15.9%, 28.3%, and 42.7% for S1, S2, and S3, respectively. Under the same water stress conditions, the aboveground biomass of the sweet sorghum decreased with increasing salt stress (Figure 4).

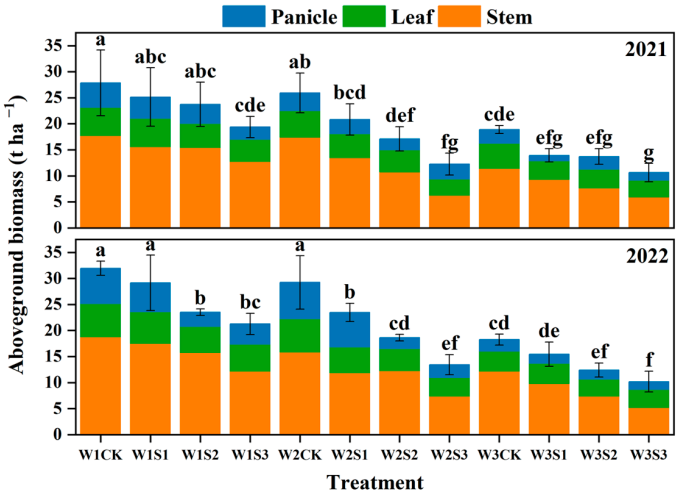


Figure 4. Aboveground biomass accumulation and distribution of sweet sorghum in 2021 and 2022 (n = 9). Different letters indicate significant differences between treatments at a level of α = 0.05 with Duncan's multiple range test. Error bars represent standard deviation.

3.5. Sugar Content

In 2021, the total sugar content of the sweet sorghum stems and the sugar content of the bottom, middle, and top parts of the stems were significantly affected by salt stress. In 2022, the total sugar content of the sweet sorghum stems and the sugar content of the bottom and top parts of the stems were significantly affected by salt stress. Water stress had a significant effect on the sugar content of the bottom part of the stem in 2022, while the total sugar content of the stem was not significantly affected by water stress. Additionally, water–salt interactions had no significant effects on the sugar content of sweet sorghum stems (Table S5).

The sugar content in the top stems > the sugar content in the middle stems > the sugar content in the bottom stems. Compared with CK, the sugar content in S1, S2, and S3 decreased by 6.3%, 8.8%, and 12.8%, respectively, based on the average values from both 2021 and 2022. Under the same water stress conditions, the sugar content in the sweet sorghum stems decreased with the increase in salt stress (Figure 5).

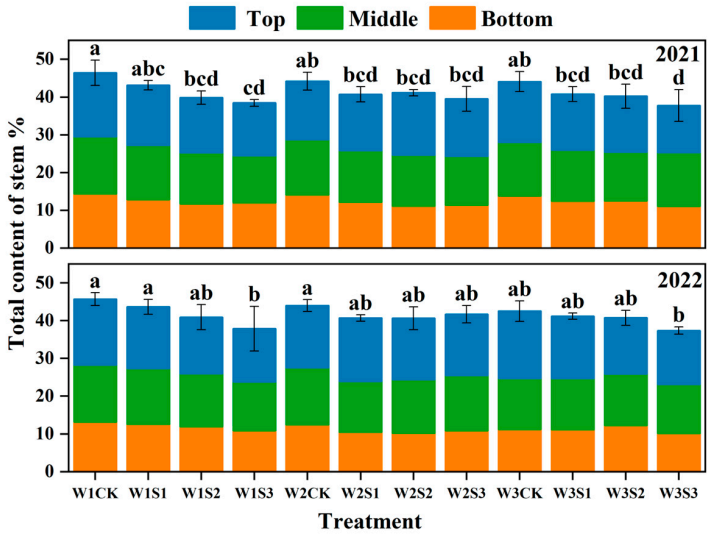


Figure 5. Total sugar content and distribution of sweet sorghum stems in 2021 and 2022 (n = 9). Different letters indicate significant differences between treatments at a level of α = 0.05 with Duncan's multiple range test. Error bars represent standard deviation.

3.6. Comprehensive Analysis

The PCA and correlation matrix analyses comprehensively highlight the interrelationships between environmental factors (irrigation quota and salinity) and sweet sorghum traits, emphasizing their combined effects on growth, photosynthetic efficiency, biomass, and sugar content. The PCA results reveal that the plant height, stem diameter, aboveground biomass, and sugar content strongly contribute to the first principal component (PC1), which explains most of the variation (86.1%), while photosynthetic parameters like net photosynthetic rate (Pn), stomatal conductance (Gs), and chlorophyll content (SPAD) positively align with these traits. Conversely, the intercellular CO_2 concentration (Ci) shows a negative association, indicating stress-induced photosynthetic inefficiencies. The correlation matrix further corroborates these findings, showing strong positive correlations between the irrigation quota, growth traits, and photosynthetic efficiency, whereas salinity (EC) negatively impacts these variables, reducing the emergence rate, biomass, and sugar content (Figure 6).

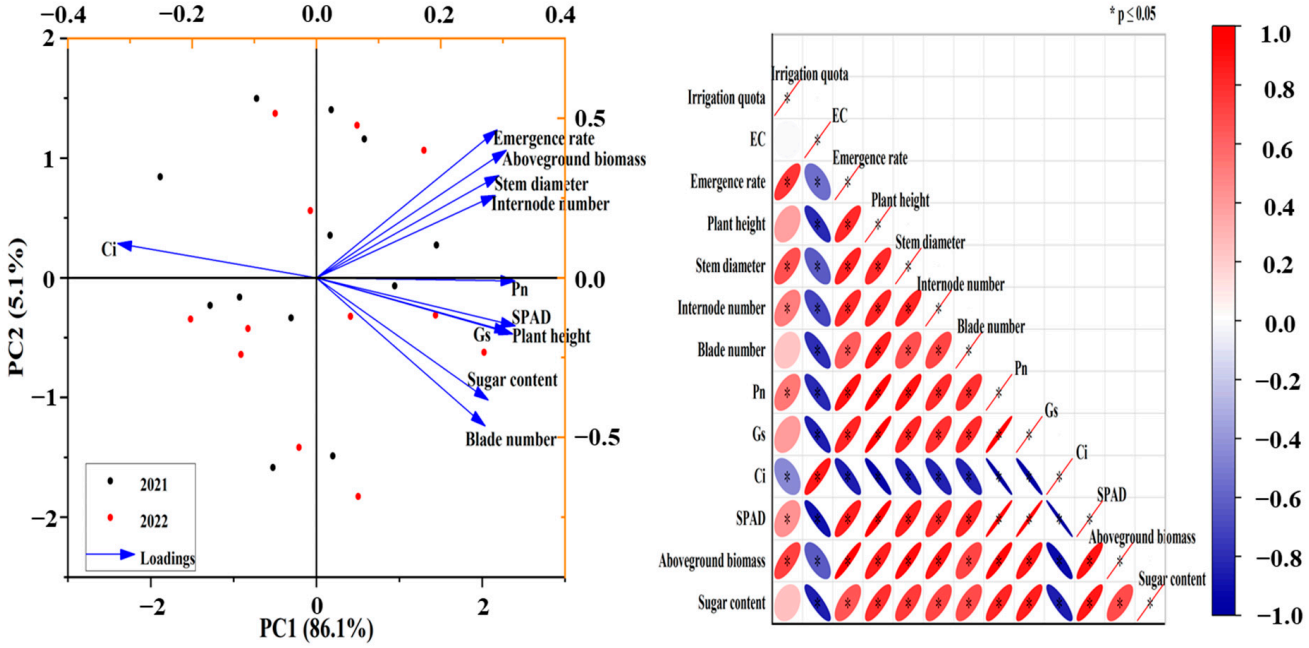


Figure 6. The Principal Component Analysis (PCA) and correlation matrix illustrating the relationships between environmental factors (irrigation quota and salinity), growth characteristics (plant height, stem diameter, internode number, and blade number), photosynthetic parameters (Pn, Gs, Ci, and SPAD), aboveground biomass, and sugar content in sweet sorghum during the 2021 and 2022 growing seasons. The PCA biplot (**left**) shows the loadings and distribution of the variables across the first two principal components (PC1: 86.1%, PC2: 5.1%). The correlation matrix (**right**) reveals significant relationships (* $p \leq 0.05$) between key variables, with positive correlations shown in red and negative correlations in blue.

4. Discussion

4.1. Emergence Rate and Growth Characteristics

Firstly, the results for the seedling emergence rate and relative salt damage rate showed that the growth of sweet sorghum was significantly affected by water and salt stress. With the increase in water and salt stress, the emergence rate of the sweet sorghum decreased, which was basically consistent with the results of previous studies in indoor germination tests and field tests [14,21,22]. Germination is the starting point of all crop growth and development processes, and is profoundly impacted by water and salt stress [23–25]. Salt and drought stress reduce the emergence rate and biomass by affecting water and nutrient absorption. Salt stress causes osmotic stress and ion toxicity, which inhibits seed water

uptake, thereby affecting seed germination and early seedling growth [26,27]. Drought stress further exacerbates water deficits by reducing water availability, leading to insufficient cell turgor, thus inhibiting biomass accumulation [28,29]. Given these mechanisms, the significant reductions in the emergence rate and biomass under salt and drought stress in sweet sorghum is logical. This study also found that the overall germination rate of sweet sorghum in 2022 was higher than that in 2021 (Table 1). This is mainly attributed to the higher rainfall in May 2022 than in 2021, for effective water supplementation during germination would improve the germination rate of sweet sorghum [30]. The PCA results corroborate this finding, as the plant height, stem diameter, and internode number were the most significant contributors to the PC1, indicating their critical role in sweet sorghum's growth and overall productivity. This suggests that more attention should be paid to water and salt management in the germination stage of sweet sorghum to improve its stress resistance and survival rate.

Secondly, the growth traits analysis revealed that the plant height, stem diameter, internode number, and blade number of the sweet sorghum were influenced by water and salt stress (Table S2). There were significant differences in the stem diameter between different water treatments (Figure 2), suggesting that drought stress may be detrimental to assimilate accumulation and storage, which could potentially affect nutrient transport and redistribution [30]. According to previous studies, under conditions of adequate water, the transfer of nutrients from the stem to the grain tends to be larger, whereas under severe drought stress, the transfer of nutrients is smaller and slower [31]. This difference may help explain the observed reduction in stem diameters under water stress, although further anatomical studies are required to confirm these effects. In addition, the plant height, stem diameter, internode number, and blade number were significantly different among the different salt treatments (Figure 2), which affected the yield and growth structure of the sweet sorghum. This is because salt stress causes plant growth retarding, inhibits the growth and differentiation of plant tissues and organs [32], and also reduces the leaf greenness index and photosynthetic efficiency, resulting in slow leaf growth [16]. Previous studies have found that the addition of nitrogen can alleviate the effects of water and salt stress on the growth of sweet sorghum [33]. The correlation matrix further emphasizes this interaction, showing strong positive correlations between the irrigation quota and growth traits, while salinity (EC) negatively correlates with the plant height, stem diameter, and emergence rate, highlighting the need for precise water and salinity management to optimize growth. Therefore, considering the changes in growth traits under different water and salt conditions is essential when formulating appropriate fertilization strategies for cultivating sweet sorghum.

4.2. Biomass Accumulation

The analysis of the aboveground biomass indicated that the biomass of the sweet sorghum was significantly affected by water and salt stress. As the water and salt stress increased, the aboveground biomass of the sweet sorghum significantly decreased, directly impacting its yield (Figure 4). Similarly, Ioannis Vasilakoglou et al. [14] found that under the condition of high soil salinity (6.9 d/S), the dry biomass of sweet sorghum decreased by 42–58%. Some studies have also found that an increase in the external NaCl concentration will reduce the leaf growth and leaf area of sorghum, resulting in a decline in the biomass yield [34]. The decrease in sorghum yield caused by the increase in soil salinity may be partly due to the decreases in both chlorophyll content and photosynthetic efficiency [16]. The decrease in sweet sorghum biomass caused by the decrease in water stress may be related to decreases in the photosynthetic efficiency, stomatal closure, and leaf K/Na ratio [14,15]. The PCA results confirm the strong contribution of biomass to the PC1, and the correlation matrix highlights the significant positive relationships between the biomass and the plant height and photosynthetic efficiency (Pn and SPAD), demonstrating their central role in determining sweet sorghum productivity. Studies have shown that the plant height, stem diameter, internode number, and stem dry mass of sweet sorghum are

significantly positively correlated with the biomass [35], where the correlation between the plant height and biomass is the strongest [36,37], indicating that these growth characteristics are key indicators of biomass production. Effective irrigation and salinity management strategies are essential to mitigate the adverse effects of stress on biomass yields.

4.3. Sugar Content

Our analysis showed that salt stress significantly impacted the stem sugar content of sweet sorghum, with a trend towards decreasing sugar content as the salt stress increased (Figure 5). Under greenhouse conditions, Almodares et al. [38] also observed a 21% decrease in the sugar content in sweet sorghum with increased salinity. This finding is consistent with previous research, indicating that salt stress inhibits sugar accumulation by disrupting metabolic processes [17]. Interestingly, water stress did not significantly affect sugar content, aligning with the results of Miller and Ottman [39], who found that water stress did not impact the sugar concentration of sweet sorghum. Although the direct impact of drought stress on sugar content was less significant than that of salt stress in this study, it may indirectly affect sugar accumulation by altering the plant's water balance and impacting its photosynthetic efficiency [28,29]. The PCA biplot underscores the close association of sugar content with other productivity traits, such as biomass and photosynthetic parameters, reinforcing the conclusion that optimal water and salinity management is vital for maximizing sugar yields. In some cases, drought stress may activate certain metabolic pathways, temporarily increasing sugar accumulation to cope with stress conditions [40,41]. However, as stress intensifies, plant metabolism gradually weakens, possibly leading to reduced sugar content [42,43]. This suggests a complex interaction between the water supply and sugar metabolism. The effects of salt stress on stem sugar content primarily occurs through two mechanisms: First, salt stress affects photosynthesis, reducing the accumulation of photosynthetic products and ultimately decreasing sugar synthesis [27,44]. Second, salt stress causes osmotic stress and ion imbalances, disrupting the transport and metabolism of carbohydrates, which hinders sugar accumulation [45,46]. Thus, under higher salt stress conditions, the sugar content in the stem gradually decreases [16,47]. The combined effects of salt and drought stress often exacerbate these negative impacts. Drought further exacerbates the osmotic pressure caused by salt stress, reducing the efficiency of water and nutrient uptake and leading to decreased sugar accumulation [27,45]. Under these stress conditions, the metabolic balance of the plant is disrupted, prioritizing the limited resources for survival rather than sugar accumulation, which explains the observed reduction in sugar content [44,48].

4.4. Photosynthetic Characteristics and Their Role in Biomass and Sugar Content Accumulation

The photosynthetic characteristics of sweet sorghum, including the net photosynthetic rate (Pn), stomatal conductance (Gs), intercellular CO_2 concentration (Ci), and chlorophyll content (SPAD), were significantly impacted by increased water and salt stress, as shown in Figure 3. These photosynthetic parameters are directly linked to the plant's growth and yield since photosynthesis is the primary source of assimilates required for biomass production and sugar accumulation. As the water and salt stress increased, reductions in the Pn and Gs were observed, which subsequently hindered both biomass production and sugar synthesis. The correlation matrix further highlights the strong positive relationships between the Pn, SPAD, and biomass, while the negative correlation of Ci with these traits suggests that stress-induced inefficiencies in photosynthesis significantly affect both growth and sugar accumulation. This decrease in photosynthetic activity under salt stress can be attributed to osmotic stress and ion toxicity, which reduce the chlorophyll content, limit stomatal opening, and disrupt enzyme activities in the Calvin cycle [27,44].

The pronounced reduction in stomatal conductance (Gs) and net photosynthetic rate (Pn), especially in the W3S3 treatment, highlighted the severe constraints on carbon assimilation under combined salt and drought stress. The reduced stomatal conductance under these conditions is likely a physiological response to minimize water loss, but it also

limits CO_2 availability, thereby restricting the photosynthetic rate and consequently the biomass accumulation [43]. The significant decline in the Pn under high salt conditions (W3S3) highlights that sweet sorghum's photosynthetic efficiency is highly sensitive to both water and salt stress, which in turn affects its growth and productivity.

Interestingly, the increase in the Ci under drought and salt stress may reflect the restricted CO_2 flow caused by the reduction in stomatal conductance (Gs), combined with the decreased photosynthetic rate (Pn), which reduces CO_2 consumption. This dual effect likely leads to the accumulation of intercellular CO_2. Furthermore, the impaired activity of the enzymes in the Calvin cycle or the insufficient supply of ATP and NADPH may further limit the plant's ability to effectively utilize CO_2, thereby affecting carbon fixation. This mechanism effectively explains the observed declines in the biomass and sugar content under drought and high salt conditions, as the reduced photosynthetic efficiency directly limits the supply of carbohydrates necessary for growth and sugar accumulation.

The decrease in SPAD values under increasing salt and water stress also provides evidence for a negative impact on photosynthesis, as chlorophyll content is crucial for light absorption and energy conversion during photosynthesis. Declining chlorophyll content diminishes light absorption, ultimately reducing photosynthetic efficiency [16]. The findings indicate that managing both water and salt levels is critical for maintaining chlorophyll content, optimizing photosynthesis, and ultimately achieving a higher biomass and sugar yield in sweet sorghum.

Overall, the data on photosynthetic characteristics reveal that water and salt stress not only directly impact growth parameters such as plant height and biomass, but also fundamentally affect physiological processes that are critical for biomass production and sugar synthesis. The observed reduction in photosynthetic efficiency highlights the need for careful management of irrigation and salinity to optimize photosynthetic performance, which is essential for enhancing biomass and sugar accumulation in sweet sorghum.

5. Conclusions

This study demonstrated that water and salt stress significantly impacted the emergence rate, plant growth characteristics, photosynthetic efficiency, biomass accumulation, and sugar content of sweet sorghum. Specifically, under increased water and salt stress, the emergence rate decreased by 11.0–36.2%, and the aboveground biomass was reduced by 15.9–43.8%. Salt stress markedly reduced the stem sugar content by 6.3%, 8.8%, and 12.8% under S1, S2, and S3 conditions, respectively, compared to CK. Photosynthetic efficiency, including the net photosynthetic rate (Pn), stomatal conductance (Gs), and chlorophyll content (SPAD), was significantly affected, leading to reductions in both biomass and sugar content. This study underscores the critical role of effective water and salinity management in preserving photosynthetic performance, increasing biomass yield, and optimizing sugar accumulation, thereby supporting the sustainable cultivation of sweet sorghum in arid and saline environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14122321/s1, Table S1: Variance analysis of emergence rate of sweet sorghum under different water and salt stress treatments; Table S2: Variance analysis of plant height, stem diameter, internode number, and blade number of sweet sorghum under different water and salt stress treatments; Table S3: Variance analysis of net photosynthetic rate (Pn), stomatal conductance (Gs), intercellular CO_2 concentration (Ci), and SPAD of sweet sorghum under different water and salt stress treatments; Table S4: Variance analysis of stem, leaf, panicle, and total aboveground biomass of sweet sorghum under different water and salt stress treatments; Table S5: Variance analysis of sugar content of sweet sorghum under different water and salt stress treatments.

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