Effect of Drought stress and Zinc Foliar Application on fresh biomass yield and Quality of Three Barley Cultivars

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Abstract

A field experiment was conducted during the two winter seasons of 2024–2025 and 2025–2026 at the experimental field of the Extension Farm in Al-Mahnaweiyah, affiliated with the Agricultural Extension and Training Center in Babylon, located approximately 15 km north of Babylon city. The study aimed to evaluate the effects of water stress and foliar zinc application on the green forage yield and quality of three barley cultivars (*Hordeum vulgare* L.).

The experiment was conducted using a RANDOMIZED COMPLETE BLOCK DESIGN (RCBD) in a split-split plot arrangement with three replications. Water stress was assigned to the main plots at three levels: 100% irrigation applied at 50% depletion of available water (control treatment) (S1), 80% of the irrigation water amount applied in the control treatment (S2), and 65% of the irrigation water amount applied in the control treatment (S3).Foliar zinc application was assigned to the subplots at three levels: 0, 0.4, and 0.8 kg Zn ha^{-1}, whereas the three barley cultivars—Buhuth 244, Ibaa 99, and Ibaa 265—were assigned to the sub-subplots. The results showed that the full irrigation treatment (S1; control) significantly outperformed the other treatments in green forage yield, recording the highest mean values of 32.09 and 35.24 t ha^{-1} in the first and second seasons, respectively. Foliar application of zinc at 0.8 kg Zn ha^{-1} also produced the highest mean green forage yields of 28.30 and 31.14 t ha^{-1}, while the cultivar Buhuth 244 recorded the highest values of 26.97 and 29.80 t ha^{-1} in the two respective seasons. Regarding crude protein content, the full irrigation treatment and the cultivar Buhuth 244 were superior only in the first season, recording 18.17% and 18.36%, respectively. In contrast, foliar application of zinc at 0.8 kg Zn ha^{-1} resulted in the highest crude protein percentages in both seasons, reaching 18.24% and 24.37%, respectively. For crude fiber content, the severe water-stress treatment S3 produced the highest mean values of 28.70% and 27.39% in the two seasons, respectively. Likewise, zinc application at 0.8 kg Zn ha^{-1} recorded the highest means of 27.76% and 26.58%. The cultivar Ibaa 265 was superior, with mean values of 27.37% and 26.30% in the first and second seasons, respectively. With respect to plant zinc concentration, the S3 water-stress treatment recorded the highest mean values of 40.18 and 30.88 mg kg^{-1} in the two seasons, respectively. Foliar zinc application at 0.8 kg Zn ha^{-1} also achieved the highest mean concentrations of 37.74 and 30.94 mg kg^{-1}. Furthermore, the cultivar Ibaa 265 exhibited the highest zinc concentrations, recording 35.92 and 30.94 mg kg^{-1} in the first and second seasons, respectively.

Keywords: Water stress, zinc, green forage, barley.

Introduction

Barley (*Hordeum vulgare* L.) is considered the most important winter forage cereal crop in Iraq. It is used as green forage and for seed production, with the grains being incorporated into concentrated feed formulations for livestock and poultry. Barley grains are

ISSN 2072-3857

also used in the production of brown bread **[1]**.

In Iraq, barley is commonly irrigated by surface flooding in basins or strips. However, this irrigation method often results in inadequate control over water distribution within the field, leading to substantial water losses through infiltration, deep percolation, drainage, and evaporation. It may also cause an uneven distribution of soil moisture within the root zone, which can occasionally result in poor soil aeration. Moreover, chemical fertilizers, particularly nitrogen fertilizers, may be susceptible to leaching beyond the root zone. Consequently, water- and fertilizer-use efficiencies decline, although improving these efficiencies is a fundamental objective of irrigation management, especially in arid and semi-arid regions.

Barley crops grown under irrigated conditions may be exposed to water stress because of fluctuations in water availability or water scarcity during the growing season. Deficit irrigation may also be deliberately adopted by reducing the amount of water supplied to the crop to improve water-use efficiency. Therefore, the adoption of appropriate field practices, including the cultivation of different barley cultivars, is essential **[2]**. Crop yield under water-deficit conditions reflects both the cultivar's response to water stress and its capacity to maintain high productivity, depending on the crop growth stage and the intensity and duration of the stress **[3]**. Grain yields have increased in recent decades without a substantial increase in crop evapotranspiration, indicating that crop-management practices that alleviate growth constraints under water-deficit conditions can improve the efficiency with which crops use water and nutrients**[4]**.

Micronutrient deficiency, particularly zinc deficiency, is an important constraint that reduces crop yield and quality. Several researchers have reported that zinc deficiency is among the most widespread micronutrient deficiencies affecting cereal crops **[5]**. Therefore, zinc fertilization may result in considerable increases in grain and straw yields. In Iraq, **[6]** reported that 83% of soil samples collected from different regions of the country contained low levels of available zinc and that crops grown in these soils responded positively to zinc application.

This study aimed to determine the response of barley cultivars to water stress and foliar zinc application by reducing irrigation water amounts at different stages of plant development and evaluating the resulting effects on green forage yield and quality.

Materials and Methods

A field experiment was conducted during the winter growing seasons of 2024–2025 and 2025–2026 at the experimental field of the Extension Farm in Al-Mahnaweiyah, affiliated with the Agricultural Extension and Training Center in Babylon, approximately 15 km north of Babylon.

Random soil samples were collected from different locations within the experimental field at a depth of 0–40 cm after removing the upper 5 cm of the soil surface. The samples were thoroughly mixed to obtain a homogeneous composite sample, air-dried, crushed, and passed through a 2-mm sieve. A representative subsample was then taken to determine selected physical and chemical properties of the experimental soil (Table1).

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Table 1. Selected physical and chemical properties of the experimental field soil and irrigation water at a soil depth of 0–0.40 m

No.	Property	Sample/Component	Value	Unit
1	pH	Soil	7.2	—
		Irrigation water	7.5	—
2	Electrical conductivity (EC)	Soil	3.2	dS m^{-1}
		Irrigation water	2.2	dS m^{-1}
3	Organic matter (O.M.)	Soil	0.53	g kg^{-1}
4	Total porosity	Soil	41	%
5	Bulk density	Soil	1.26	Mg m^{-3}
6	Potassium	Available in soil	153	Ppm
		Dissolved in irrigation water	8.3	Ppm
7	Phosphorus	Available in soil	7.2	Ppm
		Dissolved in irrigation water	6.3	Ppm
8	Nitrogen	Available in soil	44.7	Ppm
		Dissolved in irrigation water	15.6	Ppm
9	Soil particle-size distribution	Sand	51.6	g kg^{-1}
		Silt	608.4	g kg^{-1}
		Clay	340.0	g kg^{-1}
10	Soil texture	Silty clay loam	—	—
11	Available zinc in soil	Soil	0.41	mg kg^{-1}

A RANDOMIZED COMPLETE BLOCK DESIGN (RCBD) arranged in a split–split plot design with three replications was used. The experimental unit area was 4 m^2 (2 × 2 m). The experiment included three factors. Water stress was assigned to the main plots at three levels: 100% irrigation applied after depletion of 50% of the available soil water (control treatment) (S1), 80% of the irrigation water amount applied in the control treatment (S2), and 65% of the irrigation water amount applied in the control treatment (S3). Foliar zinc application was assigned to the subplots at three levels: 0, 0.4, and 0.8 kg Zn ha^{-1}. Zinc was applied in two equal doses at the tillering and booting growth stages. The sub-subplots were assigned to three barley cultivars: Buhuth 244 (V1), Ibaa 99 (V2), and Ibaa 265 (V3). The data were statistically analyzed using analysis of variance (ANOVA) at the 0.05 probability level. Treatment means for each studied trait were compared using the least significant difference (LSD) test at the 0.05 probability level **[7]**. Following data collection, the statistical analysis was performed using GenStat, version 20, according to the procedure described by **[8].**

ISSN 2072-3857

The experimental field was prepared by plowing, harrowing, and leveling. It was then divided into experimental units, each consisting of 10 rows spaced 20 cm apart. Barley seeds were sown at a seeding rate of 140 kg ha^{-1} **[9]**. Diammonium phosphate fertilizer (DAP, 18–46–0) was applied at a rate of 160 kg ha^{-1} during land preparation. Urea fertilizer containing 46% N was applied at a rate of 40 kg ha^{-1} in two equal doses: the first at sowing and the second 40 days after seedling emergence.

Irrigation was carried out using a network of plastic pipes connected to a gasoline-powered pump. A water meter was installed on the pump discharge pipe to measure the amount of water applied. At sowing, equal amounts of water were supplied to all experimental plots until the soil moisture content reached field capacity. Soil moisture content was continuously monitored using a soil moisture meter (Model PMS-714, Lutron Electronic Enterprise Co., Ltd.) after calibrating the device against the gravimetric method of soil moisture determination.

Irrigation was repeated after the depletion of 50% of the available soil water within a soil depth of 0.40 m. The amount of water required to restore soil moisture to field capacity was then applied separately to each experimental unit of the full-irrigation treatment according to the equation proposed by **[10]**.

$$w = a \times \ell b \left(\frac{\%Pw^{f.c} - Pw^{w}}{100} \right) \times D$$

where:

- W = volume of water to be added during irrigation (m^{-3}).
- A = irrigated area (m^{-2});
- ℓb = bulk density ($mcg.m^{-3}$).
- $Pw^{f.c}$ = Percentage of soil moisture based on weight at field capacity (after irrigation).
- Pw = Percentage of soil moisture before irrigation.
- D = the depth of the soil to be irrigated in meters Seasonal water use.
- Accordingly, the amount of irrigation water applied to the full-irrigation treatment (S1) was 169 L per experimental unit, whereas 135 and 110 L were applied to treatments S2 and S3, respectively.

Studied Traits

Green Forage Yield at Flowering

An area of 2 m² from the inner rows of each experimental unit was harvested at a height of 6–8 cm above the soil surface **[11]**. The harvested forage was weighed immediately to minimize moisture loss through evaporation, and the recorded weight was converted to tonnes per hectare.

Crude Protein Percentage in Green Forage

A 0.2-g sample of dried and ground forage was digested, and its nitrogen percentage was determined using the Kjeldahl method with a Micro-Kjeldahl apparatus in the laboratories of the Department of Field Crops. The crude protein percentage was calculated using the following equation:

Crude protein percentage in forage = nitrogen percentage in forage × 6.25 **[12]**.

The crude fiber percentage was determined according to the standard procedure described by the Association of Official Analytical Chemists **[13]**.

ISSN 2072-3857

Zinc Concentration in the Plant

A 0.2-g sample of dried and ground flag-leaf tissue was used to determine plant zinc concentration according to the method described by .**[14**]

Results and Discussion

Green Forage Yield (t ha^{-1})

The statistical analysis presented in Table 2 indicated that water stress, foliar zinc application, and barley cultivars had significant effects on green forage yield during both growing seasons. Water stress significantly affected green forage yield.

The full-irrigation treatment, S1 (control), produced the highest mean yields of 32.09 and 35.24 t ha^{-1} in the first and second seasons, respectively. In contrast, the severe drought stress treatment, S3, recorded the lowest mean yields of 16.06 and 18.06 t ha^{-1} in the respective seasons. The reduction in green forage yield under water stress may be associated with decreases in the overall photosynthetic rate and plant water potential as the intensity of water stress increases **[15]**. Reduced dry-matter accumulation under water-deficit conditions may also result from decreases in leaf area and plant height, both of which are adversely affected by water stress **[16]**.

The reduction in green forage yield may also be attributed to an imbalance in the soil water–air relationship, which decreases photosynthetic activity and disrupts the balance among plant hormones and biological processes in different plant organs **[17]** These findings agree with those reported by **[18]** and **[19]**, who indicated that water stress reduces dry-matter production and consequently decreases green forage yield.

Foliar zinc application also had a significant effect on green forage yield. The highest zinc application rate of 0.8 kg Zn ha^{-1} produced the highest mean yields of 28.30 and 31.14 t ha^{-1} in the first and second seasons, respectively. This response may be attributedto the higher zinc concentration in the spray solution, which increased the amount of the nutrient available for absorption by the plant **[20]** and **[21]** who reported that increasing the zinc concentration applied through foliar spraying increased zinc accumulation and green forage yield.

Significant differences were also observed among the barley cultivars in their responses to the experimental conditions. The cultivar Buhuth 244 significantly outperformed the other cultivars, producing the highest mean green forage yields of 26.97 and 29.80 t ha^{-1} in the first and second seasons, respectively. These results are consistent with those of **[22]** who reported that cultivars differ in green forage production because of genetic variation in their capacity to produce tillers. The interaction between water stress and foliar zinc application significantly affected green forage yield in both seasons. The combination of full irrigation, S1, and foliar zinc application at 0.8 kg Zn ha^{-1} produced the highest mean yields of 36.56 and 39.99 t ha^{-1} in the first and second seasons, respectively.

A significant interaction between water stress and barley cultivars was also observed in both seasons. The combination of full irrigation, S1, and the cultivar Buhuth 244 recorded the highest mean

ISSN 2072-3857

green forage yields of 34.99 and 38.80 t ha⁻ ¹ in the respective seasons.

Similarly, the interaction between foliar zinc application and barley cultivars was significant in both seasons. Foliar application of zinc at 0.8 kg Zn ha⁻ ¹ combined with the cultivar Buhuth 244 produced the highest mean yields of 31.64 and 34.82 t ha⁻ ¹ in the first and second seasons, respectively. However, the three-way interaction among water stress, foliar zinc application, and barley cultivars had no significant effect on green forage yield in either growing season. (Table 2&3).

Table 2. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on green forage yield (t ha⁻ ¹) during the first growing season (2024–2025)

Treatments / Irrigation level effects		**Foliar Zn application (kg Zn ha⁻ ¹)**	**cultivars**			**Irrigation × Zn mean**
			Buhuth 244	**Ibaa 99**	**Ibaa 265**	
Irrigation × Zn × cultivar	S1	Control	29.86	27.86	26.74	28.15
		0.4	34.30	32.42	27.92	31.54
		0.8	40.82	37.86	31.07	36.56
	S2	Control	24.03	22.73	19.25	22.01
		0.4	27.63	25.34	21.86	24.94
		0.8	31.72	30.05	24.93	28.90
	S3	Control	14.36	13.36	11.55	13.09
		0.4	17.58	16.01	13.43	15.67
		0.8	22.40	20.15	15.74	19.34
LSD (0.05)	Irrigation × Zn	—	—	—	—	**1.10**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**1.41**
Cultivar main effect	—	—	**26.97**	**25.09**	**21.38**	—
LSD (0.05)	Cultivars	—	—	—	—	**0.40**
Irrigation × cultivar	**Cultivar**	**S1**		**S2**	**S3**	**Irrigation level**	**Irrigation mean**

ISSN 2072-3857

interaction						
	Buhuth 244	34.99	27.79	18.11	S1	32.19
	Ibaa 99	32.71	26.04	16.51	S2	25.28
	Ibaa 265	28.55	22.01	13.57	S3	16.06
LSD (0.05)	Irrigation × cultivar	—	—	**1.11**	Irrigation levels	**1.10**
Zn × cultivar interaction	**Zn application**	**Buhuth 244**	**Ibaa 99**	**Ibaa 265**	—	**Zn mean**
	Control	22.75	21.32	19.18	—	21.08
	0.4 kg Zn ha^{-1}	26.50	24.59	21.07	—	24.05
	0.8 kg Zn ha^{-1}	31.64	29.35	23.89	—	28.30
LSD (0.05)	Zn × cultivar	—	—	**0.68**	Zn application	

Table 3. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on green forage yield (t ha^{-1}) during the 2025–2026 growing season

Effect / Irrigation treatment	**level**	**Foliar Zn application (kg Zn ha^{-1})**	**cultivars**			**Treatment mean**
			Buhuth 244	**Ibaa 99**	**Ibaa 265**	
Irrigation × Zn × cultivar	S1	Control	34.18	31.89	27.87	31.31
		0.4	37.88	34.51	30.86	34.42
		0.8	44.34	40.74	34.88	39.99
	S2	Control	26.00	24.42	21.03	23.82
		0.4	29.60	27.95	23.97	27.17
		0.8	35.22	32.72	26.44	31.46
	S3	Control	16.07	14.60	12.65	14.44
		0.4	20.04	18.07	15.24	17.78

ISSN 2072-3857

Effect / Irrigation level / Foliar Zn application (kg Zn ha⁻ ¹) / cultivars / Treatment mean						
			Buhuth 244	Ibaa 99	Ibaa 265	
		0.8	24.91	22.69	18.30	21.97
LSD (0.05)	Irrigation × Zn	—	—	—	—	0.53
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	0.70
Cultivar main effect	—	—	29.80	27.51	23.47	—
LSD (0.05)	Cultivar	—	—	—	—	0.19
Irrigation × cultivar	S1	—	38.80	35.71	31.21	35.24
	S2	—	30.27	28.36	23.81	27.48
	S3	—	20.34	18.45	15.40	18.06
LSD (0.05)	Irrigation level	—	—	—	—	0.41
LSD (0.05)	Irrigation × cultivar	—	—	—	—	0.44
Zn × cultivar	—	Control	25.42	23.64	20.52	23.19
	—	0.4	29.17	26.84	23.36	26.46
	—	0.8	34.82	32.05	26.54	31.14
LSD (0.05)	Foliar Zn application	—	—	—	—	0.31
LSD (0.05)	Zn × cultivar	—	—	—	—	0.40

Crude Protein Percentage in Green Forage (%)

The results presented in Table 3 indicated that water stress and barley cultivars had significant effects on the crude protein percentage of green forage during the first season only, whereas foliar zinc application had a significant effect during both growing seasons.

Water stress significantly affected the crude protein percentage of green forage. The full-irrigation treatment, S1 (control), significantly outperformed the other treatments by recording the highest mean crude protein content of 18.17% during the first season. In the second season, however, no significant differences were observed among the water-stress treatments. The significant decline in crude protein percentage with increasing water-

ISSN 2072-3857

stress intensity may be attributed to the restriction of nitrogen uptake and translocation within the plant. Water deficit may also reduce the activity of enzymes involved in nitrate reduction and the synthesis of amino acids and proteins. In addition, reduced photosynthetic efficiency limits the production of carbon compounds required for protein synthesis, thereby decreasing the protein content of green forage. **[23]** reported that water stress disrupts nitrogen metabolism and reduces protein-synthesis efficiency because of decreased nitrogen uptake and assimilation within the plant. These findings are consistent with those of **[24]**, who found that increasing water-stress intensity reduced the crude protein percentage of barley forage compared with full irrigation.

Foliar zinc application also had a significant effect on crude protein percentage. The highest zinc application level, 0.8 kg Zn ha^{-1}, significantly produced the highest mean crude protein percentages of 18.14% and 24.37% in the first and second seasons, respectively. This increase may be attributed to the essential role of zinc in activating several enzymes involved in nitrogen metabolism, particularly those associated with nitrate reduction and the synthesis of amino acids and proteins. Zinc may also improve photosynthetic efficiency and nutrient uptake, thereby increasing the protein content of green forage. **[25]** indicated that zinc plays a fundamental role in regulating nitrogen metabolism and activating enzymes responsible for protein synthesis, which positively affects crop quality. These results are consistent with those of **[26]**, who reported that zinc application improved nitrogen-use efficiency in barley and contributed to increased protein content and enhanced nutritional quality.

The same table also showed significant differences among the barley cultivars in their response to the experimental conditions during the first season only. The cultivar Buhuth 244 significantly outperformed the other cultivars in the first season, recording the highest mean crude protein percentage of 18.36%. In contrast, no significant differences among the cultivars were observed during the second season. These differences may be attributed to genetic variation among the cultivars in nitrogen-uptake and utilization efficiency, their ability to synthesize and accumulate proteins in plant tissues, and the efficiency of physiological processes associated with growth and dry-matter production. These variations were consequently reflected in the crude protein content of green forage. This finding agrees with **[27]**, who reported genetic differences among traditional barley genotypes in forage-quality traits, including protein content, as well as in agronomic characteristics. It is also consistent with **[28]**, who indicated that barley cultivars differ genetically in nitrogen-use efficiency and physiological traits related to protein accumulation, confirming the importance of cultivar genotype in determining green forage quality.

The results further demonstrated a significant interaction between water stress and foliar zinc application in both growing seasons. The combination of full irrigation, S1 (control), and foliar zinc application at 0.8 kg Zn ha^{-1} significantly produced the highest mean crude protein percentages of 18.34% and 24.82% in the first and second seasons, respectively.

The interaction between water stress and barley cultivars had no significant effect in either season. Similarly, the interaction between foliar zinc application and barley cultivars was not significant in either season. The three-way interaction among water stress, foliar zinc application, and barley cultivars also

ISSN 2072-3857

had no significant effect during either growing season (Table 4&5).

Table 4. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on crude protein percentage in green forage (%) during the first growing season (2024–2025)

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
Irrigation × Zn × cultivar	S1	Control	19.77	16.28	18.18	18.08
		0.4	17.65	17.58	18.99	18.07
		0.8	18.51	17.85	18.67	18.34
	S2	Control	17.64	16.30	18.23	17.39
		0.4	18.33	18.84	17.67	18.28
		0.8	17.52	18.45	16.54	17.50
	S3	Control	18.64	17.06	17.76	16.78
		0.4	18.83	17.62	17.77	17.82
		0.8	18.31	15.93	16.09	18.07
LSD (0.05)	Irrigation × Zn	—	—	—	—	**0.62**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**1.71**
Cultivar main effect	—	—	**18.36**	**17.32**	**17.77**	—
LSD (0.05)	Cultivars	—	—	—	—	**0.66**
Irrigation × cultivar	S1	—	18.64	17.24	18.62	**18.17**
	S2	—	17.83	17.86	17.48	**17.72**
	S3	—	18.60	16.87	17.21	**17.56**
LSD (0.05)	Irrigation levels	—	—	—	—	**0.28**
LSD (0.05)	Irrigation × cultivar	—	—	—	—	**0.95**
Zn × cultivar	—	Control	18.68	16.55	18.06	**17.54**
	—	0.4	18.27	18.01	18.14	**17.76**
	—	0.8	18.12	17.41	17.10	**18.14**
LSD (0.05)	Foliar Zn application	—	—	—	—	**0.42**
LSD (0.05)	Zn × cultivar	—	—	—	—	**1.01**

ISSN 2072-3857

Table 5. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on crude protein percentage in green forage (%) during the second growing season (2025–2026)

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
Irrigation × Zn × cultivar	S1	Control	24.03	23.66	23.41	23.70
		0.4	24.96	25.26	24.24	23.37
		0.8	23.53	22.53	24.05	24.82
	S2	Control	25.46	24.80	23.76	24.68
		0.4	21.86	21.56	23.98	22.47
		0.8	22.32	21.28	25.56	23.05
	S3	Control	25.76	24.90	23.58	24.75
		0.4	21.86	21.65	23.93	23.14
		0.8	22.51	25.69	21.22	22.48
LSD (0.05)	Irrigation × Zn	—	—	—	—	**1.16**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**3.50**
Cultivar main effect	—	—	**23.59**	**23.48**	**23.75**	—
LSD (0.05)	Cultivars	—	—	—	—	**1.36**
Irrigation × cultivar	S1	—	24.18	23.22	23.37	**23.96**
	S2	—	23.82	22.55	24.08	**23.40**
	S3	—	23.90	24.43	22.91	**23.45**
LSD (0.05)	Irrigation levels	—	—	—	—	**0.56**
LSD (0.05)	Irrigation × cultivar	—	—	—	—	**1.97**
Zn × cultivar	—	Control	25.09	24.45	23.58	**23.19**
	—	0.4	22.89	22.82	24.05	**23.26**
	—	0.8	22.79	23.17	23.61	**24.37**
LSD (0.05)	Foliar Zn application	—	—	—	—	**0.78**
LSD (0.05)	Zn × cultivar	—	—	—	—	**2.05**

Crude Fiber Percentage in Green Forage (%)

The results presented in Table 4 indicated that water stress, foliar zinc application, and barley cultivars had

ISSN 2072-3857

significant effects on the crude fiber percentage of green forage in both growing seasons. However, none of the two-way or three-way interactions had a significant effect in either season.

Water stress significantly affected crude fiber percentage. The severe water-stress treatment, S3, significantly produced the highest mean crude fiber percentages of 28.70% and 27.39% in the first and second seasons, respectively. The significant increase in crude fiber percentage with increasing water-stress intensity may be attributed to the restriction of vegetative growth under water-deficit conditions and the enhanced deposition of cell-wall components, particularly cellulose, hemicellulose, and lignin. In addition, water stress may reduce dry-matter digestibility, thereby increasing fiber content and decreasing forage quality. **[24]** reported that water stress increased fiber components, including acid detergent fiber (ADF) and neutral detergent fiber (NDF), and reduced barley forage quality because of the greater accumulation of structural cell-wall components. These findings are also consistent with those of **[29]**, who demonstrated that reduced irrigation altered barley-quality traits associated with dry matter and structural composition, and with **[28]**, who indicated that water deficit restricts growth and alters dry-matter composition in barley plants.

Foliar zinc application also had a significant effect on crude fiber percentage. The highest zinc application level, 0.8 kg Zn ha^{-1}, significantly produced the highest mean crude fiber percentages of 27.76% and 26.58% in the first and second seasons, respectively. This increase may be attributed to the physiological role of zinc in activating several enzymes involved in carbohydrate metabolism and improving photosynthetic efficiency. These processes may enhance dry-matter production and the formation of structural plant components, thereby increasing crude fiber content. **[30]** reported that zinc sulfate application improved the qualitative characteristics of barley and affected the chemical components associated with plant quality. These findings are consistent with those of **[31]**, who found that zinc fertilization improved the quality traits of cereal forage crops, including barley.

The same table also revealed significant differences among barley cultivars in their response to the experimental conditions. The cultivar Ibaa 265 significantly outperformed the other cultivars, producing the highest mean crude fiber percentages of 27.37% and 26.30% in the first and second seasons, respectively. **[32]** confirmed that barley possesses structural and nutritional characteristics associated with relatively high fiber content, which enhances its value as a forage crop. The significant differences among barley cultivars in crude fiber percentage may be attributed to genetic variation in growth efficiency, dry-matter production, and the deposition of cell-wall components, as well as differences in their responses to environmental conditions. These factors resulted in variation in crude fiber content among the cultivars. **[33]** reported that genetic differences among barley genotypes caused significant variation in forage-quality traits, including crude fiber, because of differences in genetic composition and genotype × environment interactions. These results are also consistent with those of **[27]**, who demonstrated significant variation among barley genotypes in forage-quality characteristics (Table 6&7).

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Table 6. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on crude fiber percentage in green forage (%) during the first growing season (2024–2025)

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
Irrigation × Zn × cultivar	S1	Control	24.45	26.00	27.23	25.89
		0.4	22.47	24.47	25.10	24.01
		0.8	22.13	23.30	25.00	23.48
	S2	Control	27.37	27.84	27.11	27.44
		0.4	25.36	27.07	27.15	26.53
		0.8	24.83	26.13	26.37	25.78
	S3	Control	29.60	29.51	30.73	29.95
		0.4	27.37	28.79	30.33	28.83
		0.8	26.87	27.80	27.33	27.33
LSD (0.05)	Irrigation × Zn	—	—	—	—	**1.34**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**2.52**
Cultivar main effect	—	—	**25.61**	**26.77**	**27.37**	—
LSD (0.05)	Cultivars	—	—	—	—	**0.89**
Irrigation × cultivar	S1	—	23.02	24.59	25.78	**24.46**
	S2	—	25.86	27.01	26.88	**26.58**
	S3	—	27.95	28.70	29.46	**28.70**
LSD (0.05)	Irrigation levels	—	—	—	—	**0.68**
LSD (0.05)	Irrigation × cultivar	—	—	—	—	**1.36**
Zn × cultivar	—	Control	27.14	27.78	28.36	**25.53**
	—	0.4	25.07	26.78	27.53	**26.46**
	—	0.8	24.61	25.74	26.24	**27.76**
LSD (0.05)	Foliar Zn application	—	—	—	—	**0.90**
LSD (0.05)	Zn × cultivar	—	—	—	—	**1.50**

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Table 7. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on crude fiber percentage in green forage (%) during the first growing season (2024–2025)

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
Irrigation × Zn × cultivar	S1	Control	23.21	24.80	25.43	24.84
		0.4	22.33	23.54	24.25	23.37
		0.8	21.06	22.40	23.06	22.17
	S2	Control	25.56	26.76	27.57	26.63
		0.4	24.37	25.56	26.40	25.44
		0.8	23.13	24.13	25.16	24.14
	S3	Control	27.67	28.81	29.43	28.64
		0.4	26.56	27.45	28.35	27.45
		0.8	25.11	26.13	27.01	26.08
LSD (0.05)	Irrigation × Zn	—	—	—	—	**0.74**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**1.15**
Cultivar main effect	—	—	**24.33**	**25.51**	**26.30**	—
LSD (0.05)	Cultivars	—	—	—	—	**0.38**
Irrigation × cultivar	S1	—	22.20	23.58	24.25	**23.34**
	S2	—	24.35	25.48	26.38	**25.40**
	S3	—	26.45	27.46	28.26	**27.39**
LSD (0.05)	Irrigation levels	—	—	—	—	**0.40**
LSD (0.05)	Irrigation × cultivar	—	—	—	—	**0.61**
Zn × cultivar	—	Control	25.48	26.79	27.48	**24.13**
	—	0.4	24.42	25.52	26.33	**25.42**
	—	0.8	23.10	24.22	25.08	**26.58**
LSD (0.05)	Foliar Zn application	—	—	—	—	**0.49**
LSD (0.05)	Zn × cultivar	—	—	—	—	**0.70**

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Zinc Concentration (mg kg^{-1})

The results presented in Table 5 indicated that water stress, foliar zinc application, and barley cultivars had significant effects on plant zinc concentration during both growing seasons.

Water stress significantly affected zinc concentration. The severe water-stress treatment, S3, significantly recorded the highest mean zinc concentrations of 40.18 and 30.88 mg kg^{-1} in the first and second seasons, respectively. This increase may be attributed to the reduction in cellular water content, plant growth, and dry-matter accumulation, which increased the relative concentration of ions and mineral nutrients in plant tissues because of a reduced dilution effect. Water deficit may also influence zinc uptake and translocation within the plant. **[35]** reported that water stress affects plant water relations and the physiological processes associated with zinc uptake and transport, and that zinc plays an important role in enhancing plant tolerance to drought conditions. These findings are consistent with those of **[36]**, who found that water stress in barley alters plant physiological status and mineral-ion concentrations in plant tissues through its effects on growth and water relations.

Foliar zinc application also had a significant effect on plant zinc concentration. The highest zinc application level, 0.8 kg Zn ha^{-1}, significantly produced the highest mean zinc concentrations of 37.74 and 30.94 mg kg^{-1} in the first and second seasons, respectively. This response may be attributed to the increased amount of zinc absorbed and accumulated in plant tissues following foliar application. Supplying zinc directly to the leaf surface enhances its absorption, translocation, and accumulation within plant tissues, thereby increasing its concentration compared with the untreated control.**[37]** demonstrated that foliar zinc application increased zinc absorption through the leaves and its translocation to other plant organs, while uptake and accumulation efficiencies varied among genotypes. These findings are also consistent with those of **[38]**, who reported that zinc application increased its uptake and concentration in plant tissues by improving zinc availability and accumulation within the plant.

Significant differences were also observed among the barley cultivars in their responses to the experimental conditions. The cultivar Ibaa 265 significantly outperformed the other cultivars, recording the highest mean zinc concentrations of 35.92 and 30.94 mg kg^{-1} in the first and second seasons, respectively. The significant variation among barley cultivars in plant zinc concentration may be attributed to genetic differences in zinc-uptake efficiency from the growth medium and in the ability to transport and distribute zinc within plant tissues. Some genotypes may possess more efficient mechanisms for maintaining zinc homeostasis and regulating its uptake and accumulation than others. **[39]** reported genetic variation among barley genotypes in zinc-use efficiency, as the genotypes differed in their capacity to absorb zinc and accumulate it in plant organs, which was reflected in tissue zinc concentration. These findings agree with those of **[40]**, who identified genetic variation among barley genotypes in zinc uptake and distribution because of differences in the genetic factors regulating plant zinc nutrition.

The interaction between water stress and foliar zinc application significantly affected plant zinc concentration in both growing seasons. The combination of the S3 water-stress treatment and foliar zinc application at 0.8 kg Zn ha^{-1} recorded the highest mean zinc

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concentrations of 44.91 and 32.63 mg kg^{-1} in the first and second seasons, respectively.

A significant interaction between water stress and barley cultivars was also observed in both seasons. The combination of the S3 water-stress treatment and the cultivar Ibaa 265 produced the highest mean zinc concentrations of 43.08 and 34.56 mg kg^{-1} in the first and second seasons, respectively.

Similarly, the interaction between foliar zinc application and barley cultivars was significant in both seasons. Foliar zinc application at 0.8 kg Zn ha^{-1} combined with the cultivar Ibaa 265 recorded the highest mean zinc concentrations of 40.28 and 31.85 mg kg^{-1} in the first and second seasons, respectively. The three-way interaction among water stress, foliar zinc application, and barley cultivars also had a significant effect in both growing seasons. The combination of the S3 water-stress treatment, foliar zinc application at 0.8 kg Zn ha^{-1}, and the cultivar Ibaa 265 produced the highest mean zinc concentrations of 47.57 and 36.69 mg kg^{-1} in the first and second seasons, respectively (Table 8&9).

Table 8. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on plant zinc concentration (mg kg^{-1}) during the first growing season (2024–2025)

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha^{-1})	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
Irrigation × Zn × cultivar	S1	Control	21.75	23.47	24.75	23.23
		0.4	28.18	28.16	29.47	28.60
		0.8	30.18	30.47	33.22	31.29
	S2	Control	25.25	27.13	31.98	28.12
		0.4	27.34	28.08	34.54	29.99
		0.8	34.20	36.80	40.04	37.02
	S3	Control	33.09	36.43	39.56	36.36
		0.4	36.21	39.51	42.12	39.28
		0.8	41.87	45.28	47.57	44.91
LSD (0.05)	Irrigation × Zn	—	—	—	—	**1.77**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**2.63**
Cultivar main effect	—	—	**32.81**	**30.90**	**35.92**	—
LSD (0.05)	Cultivars	—	—	—	—	**0.83**
Irrigation ×	S1	—	26.71	27.37	29.14	**27.74**

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Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
cultivar						
	S2	—	28.93	30.67	35.52	**31.71**
	S3	—	37.05	40.40	43.08	**40.18**
LSD (0.05)	Irrigation levels	—	—	—	—	**1.27**
LSD (0.05)	Irrigation × cultivar	—	—	—	—	**1.54**
Zn × cultivar	—	Control	26.70	29.01	32.09	**29.27**
	—	0.4	30.58	31.92	35.37	**32.62**
	—	0.8	35.42	37.52	40.28	**37.74**
LSD (0.05)	Foliar Zn application	—	—	—	—	**1.07**
LSD (0.05)	Zn × cultivar	—	—	—	—	**1.54**

Table 9. Effects of water stress, foliar zinc application, barley cultivars, and their interactions on plant zinc concentration (mg kg⁻ ¹) during the second growing season (2025–2026)

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
Irrigation × Zn × cultivar	S1	Control	21.03	27.11	31.03	23.79
		0.4	26.74	22.82	21.81	28.28
		0.8	27.76	32.28	26.80	28.95
	S2	Control	29.05	26.70	33.94	27.86
		0.4	27.37	30.22	29.63	29.07
		0.8	29.20	32.48	32.05	31.24
	S3	Control	25.85	25.86	30.58	27.43
		0.4	32.50	28.82	36.40	32.57
		0.8	31.73	29.46	36.69	32.63
LSD (0.05)	Irrigation × Zn	—	—	—	—	**1.62**
LSD (0.05)	Irrigation × Zn × cultivar	—	—	—	—	**2.19**
Cultivar main effect	—	—	**28.54**	**27.79**	**30.94**	—

ISSN 2072-3857

Effect / treatment	Irrigation level	Foliar Zn application (kg Zn ha⁻ ¹)	cultivars			Mean
			Buhuth 244	Ibaa 99	Ibaa 265	
LSD (0.05)	Cultivars	—	—	—	—	**0.65**
Irrigation × cultivar	S1	—	26.55	28.54	30.03	**27.01**
	S2	—	27.40	27.91	28.05	**29.39**
	S3	—	27.07	31.72	34.56	**30.88**
LSD (0.05)	Irrigation levels	—	—	—	—	**1.42**
LSD (0.05)	Irrigation × cultivar	—	—	—	—	**1.49**
Zn × cultivar	—	Control	24.67	27.20	31.70	**27.86**
	—	0.4	28.87	27.28	29.28	**28.48**
	—	0.8	29.56	31.41	31.85	**30.94**
LSD (0.05)	Foliar Zn application	—	—	—	—	**0.84**
LSD (0.05)	Zn × cultivar	—	—	—	—	**1.20**

Conclusion

The results demonstrated that water stress, foliar zinc application, and barley cultivar significantly influenced green forage yield and quality. Full irrigation produced the highest green forage yield and crude protein content, whereas severe water stress increased crude fiber and plant zinc concentration. Foliar application of zinc at 0.8 kg Zn ha⁻ ¹ improved forage yield, protein content, and zinc accumulation. Buhuth 244 was superior in forage yield and protein content, while Ibaa 265 recorded the highest crude fiber and zinc concentrations. Therefore, combining adequate irrigation with foliar zinc application at 0.8 kg Zn ha⁻ ¹, particularly for Buhuth 244, is recommended to improve barley green forage productivity and quality.

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