PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9266

eISSN 2348-1900

RESEARCH ARTICLE

Effect of exogenous proline on drought stress tolerance in wheat (*Triticum aestivum* L.) cultivars

HHA Alkhafagi[1*], YA Al-Janabi[2] & KF H Al-Khafagi[1]

[1]Department of Field Crop, College of Agriculture, Al-Qasim Green University, Iraq
[2]Department of Field Crops, College of Agriculture, University of Anbar, Iraq

*Correspondence email - haider079@agre.uoqasim.edu.iq

Received: 03 May 2025; Accepted: 17 July 2025; Available online: Version 1.0: 07 September 2025

Cite this article: Alkhafagi HHA, Al-Janabi YA, Al-Khafagi KFH. Effect of exogenous proline on drought stress tolerance in wheat (*Triticum aestivum* L.) cultivars. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9266

Abstract

Due to the scarcity of irrigation water and to achieve maximum benefit from the available irrigation water, this study investigated the impact of exogenous proline application on drought tolerance in three wheat (*Triticum aestivum* L.) cultivars and evaluated their water use under stress conditions. A factorial field experiment was conducted using a split-split plot design with three factors at three levels each. The main plot factor was drought stress, with three levels: S1 (control) involved irrigation with 50 % of the available water between field capacity (FC) and wilting point (WP); S2 represented mild drought with 30 % available water (70 % reduction); S3 represented severe drought with 10 % available water (90 % reduction). The second factor (subplot) was proline concentration: P1 (0 mg L^{-1}), P2 (25 mg L^{-1}) and P3 (50 mg L^{-1}). The third factor (sub-subplot) was wheat cultivar: Ibaa 99, Adnaniyah and Sham 6. A 90 % reduction in available water significantly decreased vegetative and yield parameters, including plant height (58.53 cm), spikes per plant (3.98), seeds per spike (37.86), total yield (3.47 tons·ha^{-1}), flag leaf area (25.75 cm^2), chlorophyll content and water use efficiency (1.6 kg grains m^{-3} water). The highest water use efficiency was recorded under 30 % available water, while the maximum grain yield (6.07 tons ha^{-1}) was achieved under 50 % available water. Foliar application of 50 mg L^{-1} proline (P3) increased grain yield and improved water use efficiency to 1.61 kg grains m^{-3} water. Although interactions between drought stress and proline concentration were not statistically significant, Sham 6 consistently outperformed Ibaa 99 and Adnaniyah across most growth and yield parameters.

Keywords: amino acid; available water; drought stress; foliar application; water consumption

Introduction

Water scarcity presents a critical challenge to global agricultural productivity, particularly in arid and semi-arid regions. Addressing this challenge requires a clear understanding of crop water requirements and the development of optimized irrigation strategies that meet plant needs without excessive water usage. Implementing measures to mitigate irrigation water deficits is vital for conserving water resources. These measures also improve soil moisture distribution around the root zone and maintain soil health (1). Drought is one of the most severe abiotic stressors affecting crop growth and productivity, often resulting in substantial agricultural losses and, in extreme cases, complete crop failure (2). Drought stress in wheat significantly increases proline content in flag leaves while reducing chlorophyll levels and grain yield (3).

Proline, a key amino acid, plays a crucial role in plant responses to drought stress. It regulates osmotic pressure, enhances antioxidant enzyme activities, improves water retention and helps in maintaining the structural integrity of flag leaf tissue. These functions collectively contribute to increased drought resistance (4). Water stress decreases chlorophyll pigments and yield components, while proline application mitigates these effects through enhanced antioxidant activities. Plants under drought stress also produce defensive enzymes like superoxide dismutase, peroxidase and catalase, which help in scavenging the reactive oxygen species and hydrogen peroxide (5).

The accumulation of compatible solutes, including proline, is a common adaptive response in plants facing drought (6). Interestingly, no significant differences were observed between 50 % and 70 % available water treatment, suggesting the possibility of conserving up to 40 % of irrigation water (7-9). Water deficits negatively impact wheat yield components such as the number of spikes, seeds per spike, 1000-seed weight and grain yield. Higher humidity levels positively influenced leaf area, spike number and yield (10, 11). Well-timed and quantitatively appropriate irrigation is essential to optimize production and water use efficiency, as it replenishes only the water deficit (12). Proper irrigation scheduling, defined as determining the timing and quantity of irrigation for maximum yield remains critical for sustainable agriculture (13, 14).

Furthermore, the application of proline increased chlorophyll a content in wheat, indicating its potential role in enhancing photosynthetic capacity (15). It was also demonstrated that proline accumulation increases with drought severity, thereby enhancing drought and heat tolerance

Additionally it was found that applying proline at a concentration of 20 mg L^{-1} positively influenced most growth stages and yield components of wheat (16).

The present study aims to further elucidate the role of exogenous proline in alleviating the adverse effects of water stress on wheat crops, optimize irrigation water usage and estimate the actual water consumption of different wheat cultivars under varying drought and proline treatment conditions.

Materials and Methods

Experimental location and soil characteristics

A field experiment was conducted during the spring growing season of 2023 at a local farm in the northern Babylon Governorate, Iraq at latitude 32.79°, longitude 44.40°. The soil was classified as clay loam, with physical and chemical properties presented in Table 1.

Experimental design

The experiment was laid out in a randomized complete block design (RCBD) with a split-split plot arrangement. The main plots consisted of water stress levels, S1 (control): 50 % available water between FC and WP. The percentage of moisture present between field capacity and wilting point S2 (mild stress): 30 % available water (70 % reduction) and S3 (severe stress): 10 % available water (90 % reduction). Subplots: proline concentrations, P1: 0 mg L^{-1}, P2: 25 mg L^{-1} and P3: 50 mg L^{-1}. Sub-subplots: wheat cultivars V1: Ibaa 99, V2: Adnaniyah and V3: Sham 6. Each treatment was replicated three times.

Irrigation and water management

The experiment was designed to assess plant response based on the principle of moisture consumption within the range of available water for plant uptake, defined by FC and WP. The soil's water retention capacity was evaluated by determining the percentage moisture content and constructing a soil moisture characteristic curve, which represents the relationship between soil water content and matric potential (Fig. 1). Different water tension forces (33, 100, 300, 500, 1000 and 1500 kPa) were applied to soil samples to establish this curve. The experimental site was planted on November 30, 2023. Irrigation water was delivered to the plots using a 2-inch pump equipped with a water meter to quantify the applied volumes. Soil moisture content was monitored using a portable soil moisture meter calibrated

Fig. 2. Moisture measuring device in the field.

Table 1. Physical and chemical properties of the field soil

Property	Value	Unit
Silt	372	gkg^{-1} soil
Clay	78 550	gkg^{-1} soil
Soil texture	Salty loam	-
Bulk density	1.55	gcm^{-3}
Field capacity	34.68	% volumetric moisture
Wilting point	12.22	% volumetric moisture
EC (electrical conductivity)	4.98	dSm^{-1}
K^+	214.45	mg·kg^{-1}
N	94.8	mgkg^{-1}

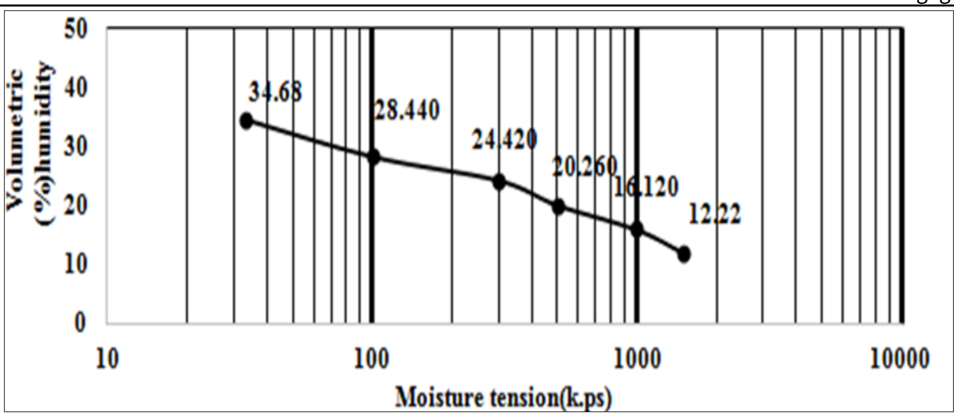

Fig. 1. Description curve of the experimental field.

against laboratory gravimetric measurements (17). Calibration ensured accurate field moisture readings (Fig. 2).

$$qv = qw \times (ab / aw) \qquad (Eqn.1) \quad ....(18)$$

Soil moisture content was expressed on both a volumetric (qv) and gravimetric (qw) basis, where qv is in $cm^3\ cm^{-3}$ and qw is in $g\ g^{-1}$.

The bulk density (ρb) of the soil was calculated as:

$$\rho b = \frac{M}{V} \ldots..(Eqn.\ 2) \ldots \ldots \ldots ....$$

ρb = Mass of dry soil (g) / volume of soil (cm^3). The density of water (ρw) is approximately 1 g cm^{-3}.

During planting, all experimental units received equal amounts of water to reach the desired water depletion level, ensuring uniform germination. Subsequently, the quantity of water to be added to each treatment to restore soil moisture to the required level was calculated based on the following equation (modified from the original presentation for clarity) (19).

$$w = a \times \ell b \left[\frac{\%Pw^{f.c} - \%Pw^{w}}{100} \right] \times \frac{D}{100} \qquad \text{(Eqn. 3)}$$

Where, W = the amount of water added (m^3)

a = experimental unit area (m^2)

ℓb = bulk density (microgram m^3)

$Pw^{f.c}$ = % moisture field capacity {after irrigation}

Pw^{w} = % moisture level before irrigation

D= irrigation water depth (m), calculated as:

D=100 (% moisture at field capacity - % moisture before irrigation) × rooting depth (m) × ρb

The water balance equation was used to calculate the water requirement of wheat.

$$ET = I + P \pm \Delta S - R - D \qquad \text{(Eqn. 4)}$$

Where, ET: actual evapotranspiration, I: depth water used in irrigation P: depth rain water (mm), D: ground water depth (equals zero because irrigation is done to the extent of field capacity, R: surface runoff (equals zero because presence of surface runoff), ΔS: humidity changes during the cultivation period until the end of the experiment.

Characteristics under study

Different characteristics such as plant height, volume of flag leaf**,** spike, seeds per plant, seed spike^{-1},total yield tons ha^{-1}, efficiency kg m^3 water ha^{-1} were studied.

Statistical analysis

All collected data were statistically analyzed using GenStat version 12. Means were compared using the least significant difference (LSD) test at a significance level of $p \leq 0.05$ (20).

Results and Discussion

Plant height

Based on the soil characteristics (Table 1) and water requirements (Table 2), the results indicated that plant height was greatest under the control treatment (Table 3) (S1: 50 % available water), as the average plant height reached 91.45 cm. Drought stress exerted a significant negative effect on plant height, with the most pronounced reduction observed under severe drought conditions (S3: 10 % available water), yielding an average height of 58.52 cm. This reduction in height under water deficit is primarily attributed to diminished cellular water content and restricted cell expansion caused by increased cell wall rigidity, which ultimately hampers plant development. Wheat seedlings subjected to water stress rapidly lose cell wall plasticity in stems

Table 2. Moisture depletion and corresponding water consumption $m^3\ ha^{-1}$

Number of irrigations	Water added $m^3\ ha^{-1}$	Depth of rain water (mm)	Depth of added water (mm)	Water consumption (m)	Depletion available water
8	3420	31	342	373	50 %
5	2510	31	251	282	70 %
3	2130	31	213	244	90 %

Table 3. Drought stress, proline, varieties and their interaction on plant height (cm)

Treatments		Cultivars			Mean	
Reduce available water	**Proline concentrations** mgL^{-1}	**V_1**	**V_2**	**V_3**	**S*P**	**S**
	P_1 (0)	88.127	86.943	89.640	88.237	
S_1 50 %	P_2 (25)	91.430	90.693	92.677	91.600	91.459
	P_3(50)	93.740	93.293	96.583	94.539	
	P_1 (0)	79.537	78.270	81.263	79.69	
S_2 70 %	P_2 (25)	83.933	83.007	85.487	84.142	85.741
	P_3 (50)	92.700	91.763	95.710	93.391	
	P_1 (0)	51.883	49.933	54.243	52.02	
S_3 90 %	P_2 (25)	59.443	57.720	59.863	59.009	58.527
	P_3(50)	63.817	62.920	66.917	64.551	
LSD 0.05			**S*P*V=** NS		**S*P=** NS	**S=**0.4441
1 Stress		**S_1**	**S_2**	**S_3**	Mean V	
	V_1	91.099	90.310	92.967	78.290	
S*V	**V_2**	85.390	84.347	87.487	77.171	
	V_3	58.381	56.858	60.341	80.265	
LSD 0.05			**S*V=** NS		**V=**0.4698	
		V_1	**V_2**	**V_3**	Mean P	
	P_1	73.182	71.716	75.049	73.316	
P*V	**P_2**	78.269	77.140	79.342	78.250	
	P_3	83.419	82.659	86.403	84.160	
LSD 0.05			**P*V=** NS		**P=** 0.2948	

and leaves, leading to reduced cell division and consequently reduced plant size (21, 22). Among the evaluated cultivars, Sham 6 exhibited the greatest plant height (80.27 cm), whereas Adnaniyah recorded the lowest (77.16 cm).

Foliar application of proline at 50 mg L^{-1} (P3) resulted in the tallest plants (84.16 cm). Exogenous proline enhances both shoot and root system development, thereby promoting increased plant height (23). In contrast, the control treatment without proline application (P1: 0 mg L^{-1}) resulted in the lowest average plant height (73.31 cm). Importantly, all interactions among the experimental factors were statistically non-significant.

Flag leaf area

Table 4 shows that there were no significant differences in flag leaf area between the S1 and S2 treatments, which recorded comparable values. However, both treatments were significantly superior to the severe drought condition (S3), which resulted in a markedly lower average flag leaf area of 25.75 cm^2. These results indicate that drought stress reduces leaf area, a phenomenon attributed to the role of the flag leaf in osmotic regulation under water deficit conditions (24).

Among the tested cultivars, Sham 6 exhibited the largest flag leaf area (38.21 cm^2), followed closely by Adnaniyah (37.68 cm^2). Application of the highest proline concentration (P3) yielded the greatest average flag leaf area (40.73 cm^2), underscoring proline's role in osmotic adjustment, dehydration tolerance and cellular protection (25, 26). In contrast, the control treatment without proline application (P1: 0 mg L^{-1}) resulted in the smallest average flag leaf area (36.06 cm^2). Notably, a significant interaction was detected between the control water treatment and the highest proline concentration (S1 × P3), producing the largest recorded flag leaf area (47.38 cm^2). All other interactions among the experimental factors (S × V, P × V, S × P × V) were statistically non-significant.

Total spikes per plant

Table 5 reveals that the total number of spikes per plant did not significantly differ between the S1 and S2 available water treatments, both of which were superior to S3, which averaged 3.98 spikes per plant. The reduction in spikes per plant under severe drought stress may be attributed to the abortion of some tillers and a decrease in their overall number. Drought stress can also reduce nutrient availability during seedling emergence and development, leading to increased competition and a lower number of fertile tillers (27-29). The Ibaa 99 cultivar recorded the

Table 4. Drought stress, proline, varieties and their interaction on flag leaf area per cm^2

Treatments		Cultivars			Mean	
Reduce available water	**Proline concentrations** mgL^{-1}	V_1	V_2	V_3	**S*P**	**S**
	P_1 (0)	41.997	41.833	42.340	42.057	
S_1 50 %	P_2 (25)	42.827	42.467	42.783	42.692	44.044
	P_3 (50)	47.477	47.033	47.640	47.383	
	P_1 (0)	41.647	41.033	41.870	41.517	
S_2 70 %	P_2 (25)	43.127	42.860	43.490	43.159	44.082
	P_3 (50)	47.620	47.340	47.753	47.571	
	P_1 (0)	24.500	24.307	25.013	24.607	
S_3 90 %	P_2 (25)	25.390	25.153	25.653	25.399	25.751
	P_3 (50)	27.250	27.140	27.353	27.248	
LSD $_{0.05}$			**S*P*V**=NS		**S*P**=0.4307	**S**=0.3468
		S_1	**S_2**	**S_3**	Mean V	
	V_1	44.100	43.778	44.254	37.981	
S*V	**V_2**	44.131	43.744	44.371	37.685	
	V_3	25.713	25.533	26.007	38.211	
LSD $_{0.05}$			**S*V=NS**		**V**= 0.1778	
		V_1	**V_2**	**V_3**	Mean P	
	P_1	36.048	35.724	36.408	36.060	
P*V	**P_2**	37.114	36.827	37.309	37.083	
	P_3	40.782	40.504	40.916	40.734	
LSD $_{0.05}$			**P*V**=NS		**P**= 0.2438	

Table 5. Drought stress, proline, varieties and their interaction on the number of spike per plant

Treatments		Cultivars			Mean	
Reduce available water	**Proline concentrations** mgL^{-1}	V_1	V_2	V_3	**S*P**	**S**
	P_1 (0)	4.183	4.137	4.277	4.19	
S_1 50 %	P_2 (25)	4.293	4.273	4.867	4.47	4.270
	P_3 (50)	5.233	5.167	5.243	5.21	
	P_1 (0)	4.170	4.170	4.253	4.19	
S_2 70 %	P_2 (25)	4.283	4.277	4.293	4.28	4.245
	P_3 (50)	4.383	4.350	4.407	4.83	
	P_1 (0)	3.887	3.870	3.920	3.892	
S_3 90 %	P_2 (25)	3.957	3.940	4.083	3.993	3.983
	P_3 (50)	4.037	4.023	4.133	4.064	
LSD $_{0.05}$			**S*P*V** = NS		**S*P** = 0.091	**S** = 0.0745
		S_1	**S_2**	**S_3**	Mean V	
	V_1	4.570	4.526	4.796	4.630	
S*V	**V_2**	4.279	4.266	4.318	4.287	
	V_3	3.960	3.944	4.046	4.386	
LSD $_{0.05}$			**S*V = NS**		**V** = 0.0560	
		V_1	**V_2**	**V_3**	Mean P	
	P_1	4.080	4.059	4.150	4.096	
P*V	**P_2**	4.178	4.163	4.414	4.252	
	P_3	4.551	4.513	4.594	4.553	
LSD $_{0.05}$			**P*V** = NS		**P** = 0.0511	

highest number of spikes per plant (4.63), while Adnaniyah had the lowest (4.28).

Proline application at 50 mg L^{-1} (P3) resulted in 4.55 spikes per plant, compared to 4.09 spikes per plant in the control proline treatment (P1). A positive interaction between the control water treatment and the highest proline concentration (S1 × P3) yielded the highest number of spikes (5.21). Conversely, the interaction between severe drought and the control proline concentration (S3 × P1) resulted in the lowest number of spikes (3.89). The remaining interactions (S × V, P × V, S × P × V) were statistically non-significant.

Number of seeds per spike

Table 6 shows that the control treatment (S1) resulted in the highest number of seeds per spike (105.45), significantly higher than the severe drought treatment (S3), which produced the lowest average of 37.86 seeds per spike. Drought-induced seed reduction may be due to tiller abortion and decreased nutrient availability during seed development (30). Among the cultivars, Sham 6 exhibited the highest number of seeds per spike (79.51), while Adnaniyah had the lowest (79.02). Proline application at 50 mg L^{-1} (P3) resulted in the highest average number of seeds per spike (80.02), compared to 78.41 seeds per spike in the control proline treatment (P1). All interactions between the experimental factors were statistically non-significant.

Total grain yield

Wheat productivity was significantly affected by water availability, as shown in Table 7. The control treatment (S1) resulted in the highest grain yield (6.07 tons ha^{-1}) (Fig. 3), while the severe drought treatment (S3) yielded the lowest (3.47 tons ha^{-1}), likely due to the reduced yield components observed (29-31). The Sham 6 cultivar recorded the highest average grain yield (5.24 tons ha^{-1}) and Adnaniyah the lowest (4.78 tons ha^{-1}).

Proline application at 50 mg L^{-1} (P3) resulted in the highest average grain yield (5.80 tons ha^{-1}), while the control proline treatment (P1) had the lowest (4.19 tons ha^{-1}), suggesting a protective role of proline under stress. A significant interaction was observed between water stress and proline application (P × S). Specifically, the combination of the control water treatment and the highest proline concentration (S1 × P3) resulted in the highest grain yield (6.87 tons ha^{-1}), demonstrating that proline accumulation enhances production under drought and heat stress by regulating osmotic pressure (32). The lowest grain yield (2.96 tons ha^{-1}) was recorded in the interaction between severe drought and the control proline concentration (S3 × P1). Drought

Table 6. Drought stress, proline, varieties and their interaction on the number of seeds per spike

Treatments		**Cultivars**			**Mean**	
Reduce available water	**Proline concentrations** mgL^{-1}	**V_1**	**V_2**	**V_3**	**S*P**	**S**
	P_1 (0)	105.027	104.590	105.143	104.920	
S_1 50 %	P_2 (25)	105.623	105.423	105.573	105.540	105.459
	P_3 (50)	105.713	105.920	106.117	105.917	
	P_1 (0)	93.660	93.327	94.123	93.703	
S_2 70 %	P_2 (25)	94.097	94.080	94.513	94.230	94.441
	P_3 (50)	95.377	94.833	95.960	95.390	
	P_1 (0)	36.653	36.337	36.830	36.607	
S_3 90 %	P_2 (25)	38.083	38.227	38.410	38.240	37.869
	P_3(50)	38.837	38.450	38.990	38.759	
LSD $_{0.05}$			**S*P*V** = NS		**S*P = NS**	**S** = 0.3574
		S_1	**S_2**	**S_3**	Mean V	
	V_1	105.454	94.378	37.858	79.230	
S*V	**V_2**	105.311	94.08	37.671	79.021	
	V_3	105.611	94.86	38.077	79.518	
LSD $_{0.05}$			**S*V = NS**		**V** = 0.2404	
		V_1	**V_2**	**V_3**	Mean P	
P*V	**P_1**	78.447	78.084	78.699	78.410	
	P_2	79.268	79.243	79.499	79.337	
	P_3	79.976	79.734	80.356	80.022	
LSD $_{0.05}$			**P*V = NS**		**P** = 0.2286	

Table 7. Drought stress, proline, varieties and their interaction on total yield tons/ha^{-1}

Treatments		**Cultivars**			**Mean**	
Reduce available water	**Proline concentrations** mgL^{-1}	**V_1**	**V_2**	**V_3**	**S*P**	**S**
	P_1 (0)	5.44	4.90	5.59	5.31	
S_1 50 %	P_2 (25)	5.96	5.95	6.20	6.04	6.07
	P_3 (50)	6.80	6.73	7.09	6.87	
	P_1 (0)	4.20	4.05	4.58	4.28	
S_2 70 %	P_2 (25)	5.46	5.40	5.83	5.57	5.40
	P_3(50)	6.26	6.19	6.64	6.37	
	P_1 (0)	2.98	2.77	3.14	2.96	
S_3 90 %	P_2 (25)	3.19	3.09	3.59	3.29	3.47
	P_3 (50)	4.08	3.92	4.46	4.15	
LSD $_{0.05}$			**S*P*V** = NS		**S*P = 0.1038**	**S = 0.0219**
		S_1	**S_2**	**S_3**	Mean V	
	V_1	6.07	5.31	3.42	4.93	
S*V	**V_2**	5.86	5.21	3.26	4.78	
	V_3	6.30	5.69	3.73	5.24	
LSD $_{0.05}$			**S*V = NS**		**V = 0.0603**	
		V_1	**V_2**	**V_3**	Mean P	
P*V	**P_1**	4.21	3.91	4.44	4.19	
	P_2	4.87	4.81	5.21	4.97	
	P_3	5.71	5.61	6.07	5.80	
LSD $_{0.05}$			**P*V = 0.1083**		**P = 0.0728**	

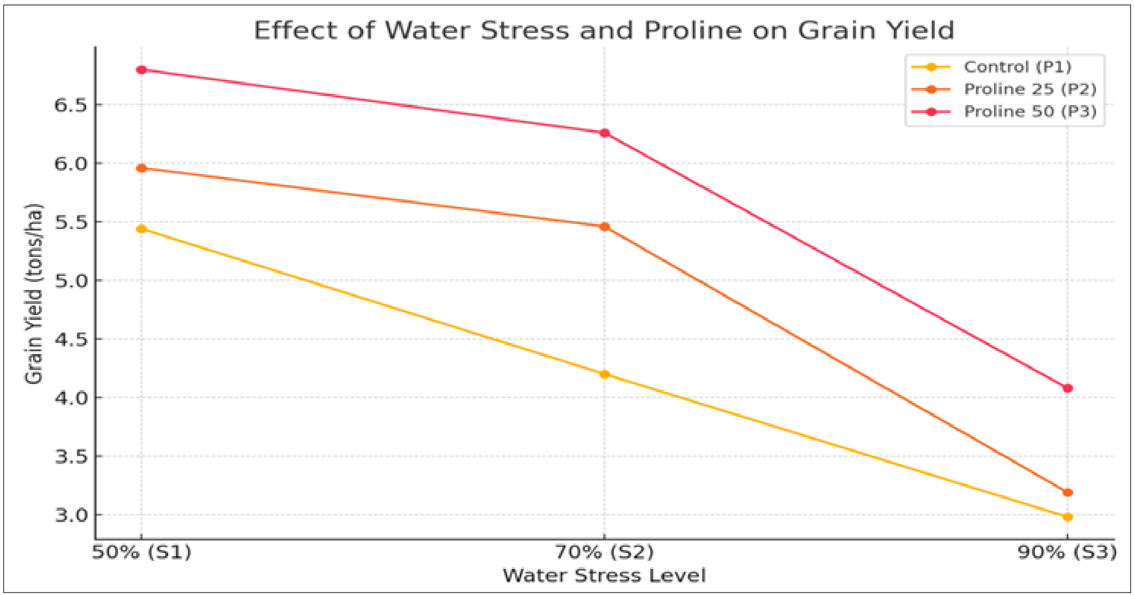

Fig. 3. Effect of water stress and proline on grain yield.

can deplete water and nutrients near wheat roots, leading to grain yield reduction (28, 33).

Water use efficiency

Table 8 demonstrates a significant increase in water use efficiency (WUE) under the mild drought treatment (S2), with an average of 2.15 kg grains m^{-3} water, compared to the control (S1). This suggests that moderate drought can enhance WUE without drastically compromising yield (34, 35). The lowest WUE was observed in the severe drought treatment (S3), averaging 1.6 kg grains m^{-3} water. Among the cultivars, Sham 6 exhibited the highest WUE (1.9 kg grains m^{-3} water), potentially due to its inherent productivity under the experimental conditions (36, 37). The Adnaniyah cultivar had a WUE of 1.7 kg grains m^{-3} water.

Proline application at 50 mg L^{-1} (P3) resulted in the highest WUE (2.16 kg grains m^{-3} water). This result was observed under the mild stress treatment (70 %), while the control proline treatment (P1) had the lowest (1.5 kg grains m^{-3} water). The interaction between the mild drought treatment and the highest proline concentration (S2 × P3) yielded the highest WUE (2.5 kg grains m^{-3} water). The lowest WUE was recorded in the interaction between severe drought and the control proline concentration (S3 × P1), reaching 1.3 kg grains m^{-3} water. Interactions between water stress and cultivars, proline concentration and cultivars and the triple interaction were statistically non-significant.

Conclusion

Reducing wheat water requirements by more than 80 % through depletion of available water is not advisable, as it significantly reduces yield. This finding is based on a study aimed at regulating the demand for irrigation water and mitigating its scarcity in Iraq, while also achieving the maximum benefit from the available water resources. However, irrigation water can be reduced to 70 % of field capacity without compromising economic viability, if proline is applied at the appropriate dosage and growth stage. Therefore, we suggest to use amino acid proline which functions as an anti-transpirants and nutrient, contributes to strengthening plant cell walls to reduce water loss from the plant.

Table 8. Drought stress, proline, varieties and their interaction on water use efficiency (kg grains m^{-3} water)

Treatments		Cultivars			Mean	
Reduce available water	**Proline concentrations** mgL^{-1}	**V_1**	**V_2**	**V_3**	**S*P**	**S**
S_1 50 %	P_1 (0)	1.5916	1.4327	1.6355	1.5533	1.7763
	P_2 (25)	1.7437	1.7407	1.8138	1.7661	
	P_3 (50)	1.9873	1.9669	2.0741	2.0094	
S_2 70 %	P_1 (0)	1.6746	1.6135	1.8260	1.7047	2.1527
	P_2 (25)	2.1766	2.1514	2.3240	2.2174	
	P_3 (50)	2.4954	2.4661	2.6467	2.5361	
S_3 90 %	P_1 (0)	1.4006	1.2989	1.4742	1.3912	1.6282
	P_2 (25)	1.4961	1.4507	1.6854	1.5441	
	P_3 (50)	1.9155	1.8388	2.0939	1.9494	
LSD 0.05			**S*P*V = 0.0135**		**S*P =** 0.0455	**S =** 0.0135
		S_1	**S_2**	**S_3**	Mean V	
S*V	**V_1**	1.7742	2.1155	1.6041	1.8313	
	V_2	1.7135	2.0770	1.5295	1.7733	
	V_3	1.8411	2.2656	1.7512	1.9526	
LSD 0.05			**S*V = NS**		**V =** 0.0257	
		V_1	**V_2**	**V_3**	Mean P	
P*V	**P_1**	1.5556	1.4484	1.6452	1.5498	
	P_2	1.8055	1.7809	1.9411	1.8425	
	P_3	2.1327	2.0906	2.2716	2.1650	
LSD 0.05			**P*V =** NS		**P =** 0.0316	

Authors' contributions

HHAA conceptualized, supervised and did the project administration. KFHAK did the formal analysis, wrote the original draft. YAAJ done the fieldwork and prepared figures. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the author used ChatGPT 4.0, for figure of the total seed yield and paraphrasing certain sections of the text to enhance clarity and coherence. After using this tool, the authors carefully reviewed and edited the content as needed and took full responsibility for the final version of the publication.

References

1. Olaposi OI, Joshua AI, Yusuf A. Development of nano irrigation system with clay diaphragm for reduced water loss in vegetable production in low income countries. Revista Espinhaço. 2017;6(1):21–28. https://doi.org/10.1007/S10311-009-0228-8
2. Arab Organization for Agricultural Development. Annual report. 2001.
3. Mahmood YA, Dsilva J, King I, Foulkes MJ. Leaf photosynthetic traits and their associations with biomass and drought tolerance in amphidiploid wheat genes and ancestors. Eur J Agron. 2023;147:126840. https://doi.org/10.1016/j.eja.2023.126840
4. Hadid ML, Ramadan MA, Elbeltagi HS, Ramadan AA, Elmetwally IM, Shalaby TA, et al. Modulation of the antioxidant defense system and nutrient content by proline higher yielding of wheat under water deficit. Notul Bot Horti Agrobot Cluj-Napoca. 2023;51(3):13291. https://doi.org/10.15835/nbha51313291
5. Ramadan KMA, El-Beltagi HS, El-Mageed TAA, Saudy HS, Al-Otaibi HH, Mahmoud MAA. The changes in various physio-biochemical parameters and yield traits of faba bean due to humic acid plus 6-benzylaminopurine application under deficit irrigation. Agronomy. 2023;13(5):1227. https://doi.org/10.3390/agronomy13051227
6. Shaaban A, Abd El-Mageed TA, Abd El-Momen WR, Saudy HS, Al-Elwany OAAI. The integrated application of phosphorous and zinc affects the physiological status, yield and quality of canola grown in phosphorus-suffered deficiency saline soil. Gesunde Pflanzen. 2023;75(5):1–9. https://doi.org/10.1007/s10343-023-00843-2
7. Shahin MG, Saudy HS, El-Bially ME, Abd El-Momen WR, El-Gabry YA, Abd El-Samad GA, et al. Physiological and agronomic responses and nutrient uptake of soybean genotypes cultivated under various sowing dates. J Soil Sci Plant Nutri. 2023;25(16):5145-58. https://doi.org/10.1007/s42729-023-01389-y
8. Al-Obaidi BSJ. Stimulating *Triticum aestivum* L. to tolerate drought [Doctoral Thesis]. University of Baghdad, College of Agriculture, Iraq; 2015.
9. Mohammad AK, Kadhim FAH. The effect of water stress on yield and its components of genetic compositions of bread wheat. Iraqi J Agric Sci. 2017;48(3):729–39. https://doi.org/10.36103/ijas.v48i3.386
10. Noha D, Ahlam J. Water stress and its relationship to some morphological and physiological characteristics of wheat plants (*Triticum* spp.) [Master Thesis]. Mentouri Fraternity University Constantine 1, Faculty of Natural and Life Sciences, Algeria; 2019.
11. Shaima SSJ. The effect of proline acid and its role in reducing the negative effect of sodium chloride on the vegetative stage of wheat plants, [Master Thesis]. Mentouri Fraternity University Constantine 1, Faculty of Natural and Life Sciences, Algeria; 2019.
12. Laskari MGM, Ilias K, Ioannis G, Christos D. Water stress effects on the morphological, physiological characteristics of maize (*Zea mays* L.) and on environmental cost. Agronomy. 2022;12(10):2386. https://doi.org/10.3390/agronomy12102386
13. Thanoon AA. The effect of irrigation scheduling using the CROPWAT program on water use efficiency, yield and its components of yellow corn (*Zea mays* L.) in semi-arid areas. Al-Rafidain Engin J. 2020;24(2):130–37. http://dx.doi.org/10.33899/rengj.2019.164329
14. Velazquez MS, Vetor CM, Carlos T, Delgado A, Acuiles CC, Suarez R. Effects of water deficit on radical apex elongation and solute accumulation in *Zea mays* L. Plant Physiol Biochem. 2022;96:29–37.
15. Altaf A, Gull S, Zhu M, Rasool G, Ibrahim MEH, Aleem M, et al. Study of the effect of PEG-6000 imposed drought stress on wheat (*Triticum aestivum* L.) cultivars using relative water content (RWC) and proline content analysis. Pak J Agric Sci. 2021;58(1):357–67. https://doi.org/10.21162/PAKJAS/21.953
16. Al-Hamoudi MAA. Response of four wheat varieties (*Triticum aestivum* L.) to concentrations of added proline under different water stress levels [Master Thesis]. College of Science, University of Karbala, Iraq; 2011.
17. Zein AK. Rapid determination of soil moisture content by the microwave oven drying method. Sudan Engin Soc J. 2002;48(40):43–54. https://doi.org/10.36103/ijas.v54i4.1788
18. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration guidelines for computing crop water requirements. FAO irrigation and drainage paper 56. FAO United Nations; 1998.
19. Kovda VA, Berg CV, Hangun RM. Drainage and salinity. FAO/UNESCO; 1973.
20. Steel RGD, Torrie JH. Principles and procedures of statistics (2nd ed.). McGraw-Hill; 1980.
21. Nikolaeva MK, Maevskaya SN, Shugaev AG, Bukhov NG. Effect of drought on chlorophyll content and antioxidant enzyme activities in leaves of three wheat cultivars varying in productivity. Russian J Plant Physiol. 2020;67(1):87–95.
22. Saqr MT. Stress physiology. College of Agriculture, Mansoura University, Egypt; 2021.
23. Bushra A, Kiran AM, Shahzad T, Sanaullah M. Mitigation of drought stress in wheat through exogenous application of proline. J Anim Plant Sci. 2023;33(6):1392–401. https://doi.org/10.36899/JAPS.2023.6.0679
24. Biswas DK, Ma BL, Morrison MJ. Changes in leaf nitrogen and phosphorus, photosynthesis, respiration, growth and resource use efficiency of a rapeseed cultivar as affected by drought and high temperature. Can J Plant Sci. 2019;99(1):111–21. https://doi.org/10.1139/CJPS-2018-0023
25. El-Hendawy BM, Al-Suhaibani S, Elshafei N, Al-Doss A, Al-Ashkar A, Ahmed AE, et al. The genetic basis of spectral reflectance indices in drought-stressed wheat. Acta Physiol Plant. 2016;38(10):227–38. https://doi.org/10.1007/s11738-016-2249-9
26. Al-Dumay BAH. Response of sunflower (*Helianthus annuus* L.) to added proline concentrations under different levels of water stress on some physiological indicators. Karbala J Agric Sci. 2018;5(1):1–15.
27. Ibrahim ME, Abdel-Aal SM, Seleiman MF, Khazaei H, Monneveux P. Effect of different water regimes on agronomical traits and irrigation efficiency in bread wheat (*Triticum aestivum* L.) grown in the Nile delta. Wheat Inf Serv. 2010;(109):P5–9.
28. Abdou SMM, Engel BA, Emam SM, El-Latif KMA. Aqua crop model validation for simulation wheat productivity under water stress condition. Comm Soil Sci Plant Anal. 2022;53(3):281–92. https://doi.org/10.1080/00103624.2021.1992981

29. Saghouri EI, Kettani IR, Ferrahi MA, Nabloussi R, Ziri NB. Water stress effect on durum wheat (*Triticum durum* L.) advanced lines at flowering stage under controlled conditions. J Agric Food Res. 2023;14:100696. https://doi.org/10.1016/j.jafr.2023.100696

30. Alemayehut KM, Kassu T, Tsegaye G. Morphological, physiological and biochemical characterization of drought-tolerant wheat (*Triticum* spp.) varieties. Int J Agron. 2021;2021:8811749. https://doi.org/10.1155/2021/8811749

31. Allah W, Iqra R, Atta MUD, Muhammad HBK, Tauqeer AY, Muhammad MJ, et al. Foliar application of putrescine alleviates terminal drought stress by modulating water status, membrane stability and yield-related traits in wheat (*Triticum aestivum* L.). Front Plant Sci. 2023;13:1000877. https://doi.org/10.3389/fpls.2022.1000877

32. Mukhtar A, Ul-Hassan F, Qadar G, Shaheen FA, Aslam MA. Response of proline accumulation in bread wheat (*Triticum aestivum* L.) under rainfed conditions. J Agric Meteorol. 2017;73(4):147–55. https://doi.org/10.2480/agrmet.D-14-00047

33. Jian-Yong W, You CX, Feng-Min L, Kadambot HMS, Neil CT. Effects of drought stress on morphophysiological traits, biochemical characteristics, yield and yield components in different ploidy wheat: A meta-analysis. Adv Agron. 2017;143:139–73. https://doi.org/10.1071/FP16082

34. Ramadan EA, El-Shawadfy MA, Osama M, Mahmoud H. Field and modeling study for deficit irrigation strategy on roots volume and water productivity of wheat. J Water Land Dev. 2021;49:129–38. https://doi.org/10.24425/jwld.2021.49.15

35. Zhuo W, Fang S, Wu D, Wang L, Li M, Zhang J, et al. Integrating remotely sensed water stress factor with a crop growth model for winter wheat yield estimation in the North China plain during 2008-2018. Crop J. 2022;10(5):1470–82. https://doi.org/10.1016/j.cj.2022.04.004

36. Xuejiao Z, Zhenwen Y, Yu S, Peng L. Differences in water consumption of wheat varieties are affected by root morphology characteristics and post-anthesis root senescence. Front Plant Sci. 2022;12:813246. https://doi.org/10.3389/fpls.2021.814658

37. Sinha R, Fritschi FB, Zandalinas SI, Mittler R. The impact of stress combination on reproductive processes in crops. Plant Sci. 2022;311:111007. https://doi.org/10.1016/j.plantsci.2021.111007

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.