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Response of Two Wheat (*Triticum aestivum* L.) Cultivars to Foliar Application of Proline on Growth, Yield, and Irrigation Water Productivity under Moderately Saline Soil Conditions

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SOIL salinity constrains wheat production across arid and semi-arid regions, yet cost-effective agronomic solutions at the field scale remain limited. This study assessed whether foliar application of the osmoprotective amino acid proline could improve growth, yield, and water use efficiency in two Egyptian wheat cultivars (*Triticum aestivum* L.) grown on salt-affected soil (ECe = 3.82 dS m^{-1}). A two-season field experiment was conducted during 2023/2024 and 2024/2025 at a private farm in Tamia, Fayoum Governorate, Egypt. Cultivars Misr-1 and Misr-3 were treated with foliar proline at 0 (control), 50, 100, and 150 ppm in a split-plot randomized complete block design with three replications. Growth parameters, physiological traits, yield components, grain chemical composition, and irrigation water productivity (IWP) for grain and total biomass were evaluated across both seasons. Among all treatment combinations, Misr-3 at 150 ppm proline recorded the highest values for plant height, flag leaf area, chlorophyll a and b contents, spike density, straw yield, grain yield, total soluble sugars, carbohydrate content, and grain protein concentration. Grain IWP reached 1.69 and 1.70 kg m^{-3} in the first and second seasons, respectively, while biomass IWP reached 2.65 and 2.67 kg m^{-3} both the highest across all treatments. Misr-1 without proline application recorded the lowest values for every evaluated parameter in both seasons. These results indicate that foliar proline at 150 ppm substantially enhanced the agronomic performance of Misr-3 under saline soil conditions, with measurable gains in yield and irrigation water use efficiency. The combination of cultivar selection and targeted proline application represents a viable, field applicable strategy for sustaining wheat production on salt-affected land in arid environments.

Keywords: Genetic variability, Osmo-protectants, Plant pigments, Salt stress, Wheat productivity.

Introduction

Wheat is the most important food grain crop on which the Egyptian people depend for their diet. Its grains are used to produce bread and pasta, while livestock farmers use wheat straw as a staple food. Egypt attaches special importance to wheat production, working to increase productivity both vertically and horizontally (Elgendy *et al.* 2024; Essa *et al.* 2026). This is achieved by encouraging farmers to grow wheat to meet steady population growth and increasing demand, thereby reducing imports and burdens on the state budget (Salem *et al*. 2022; Youssef *et al*. 2025a).

In arid climates, where extreme temperature, drought and salinity prevail, crop productivity is threatened by different eco stresses especially (Abdo *et al.* 2024).

One of the environmental elements is the salinity of t he soil. It affects the distribution and efficiency of major crops worldwide (Elkot *et al.* 2023; Saudy *et al.* 2023). Excess salt absorbed by plants is concentrated in older leaves; prolonged accumulation of this salt in the transpiration stream leads to very high concentrations of sodium and chloride ions, leading to leaf death (Helal *et al.* 2024). Otherwise, these salts may accumulate in the cell wall and cause desiccation (Munns 2005). In addition to salinity, water scarcity represents a major challenge facing agricultural production in arid regions, including Egypt (Abdelbaset *et al.* 2023;

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Ragab *et al*. 2024). With limited freshwater resources and increasing competition from other sectors, improving irrigation water productivity (IWP) has become a national priority (Helmy *et al*. 2025; Youssef *et al*. 2025b). Achieving the highest possible crop yield per unit of water applied is essential for sustainable agricultural development and food security (Dewedar *et al*. 2024; Youssef *et al*. 2023). Therefore, adopting practices that enhance both stress tolerance and water use efficiency is critical for maximizing output from every cubic meter of irrigation water.

For sustaining crop productivity and quality under different environmental pressures, various tactics and means could be adopted (Saudy *et al*., 2020b). In this regard, proline has been suggested to act as a source of nitrogen and carbon (Santos *et al*., 1996), an osmo-protectant, a metal chelator, a protein stabilizer, an inhibitor of lipid membrane peroxidation, a membrane integrity maintainer, a cytoplasmic pH maintainer, and a scavenger of reactive oxygen species (ROS) (Trovato *et al*., 2008; Hadid *et al*., 2023). It has been demonstrated that proline can increase crop growth and output at low concentrations (Serraj and Sinclair, 2002; Ali *et al*., 2007). Proline provides advantages, but if it is consumed or accumulates in large amounts, it can also have harmful effects. The use of proline at low concentrations mitigated the adverse effects of salinity on growth, while the usage of high quantities resulted in harmful effects and hindered plant growth, as described by Roy *et al.* (1993). Hair (1998) reported that the use of proline at low concentrations initiated the cycle of cytoplasmic proline synthesis from glutamate and mitochondrial proline breakdown, simultaneously delivering NADP+ to support cytoplasmic purine synthesis and reducing equivalents for mitochondrial ADP phosphorylation. In cultivars of wheat under copper stress, spraying proline at 80 mM decreased ROS production and boosted proline accumulation and protein content (Noureen *et al*., 2018). Exogenous administration of suitable osmolytes, such proline, has drawn a lot of interest in reducing the impact of stress where, it enhanced tolerance of stressed plants (Arshi *et al*. 2005). The differences between wheat cultivars were recorded in plant height, number of spikes m^{-2}, number of grains/spike, 1000-grains weight and grain yield fed^{-1} (Egyptian feddan = 4200 m^2). (Allam 2003 and El-Nagar 2003), number of leaves/plant (Mirzamasoumzadeh *et al*., 2012), number of tillers/plant (Mahdy and Teama 2000), flag leaf area (Santosh 2011and Ahmad 2013), straw yield fed^{-1} and protein percentage in grain (El-Desoky and El-Far 1999 and Allam 2003), carbohydrate percentage in grain (Mervat *et al*. 2013, Sonia and Mohammad 2013 and Emam *et al*. 2025b).

Hence, the study sought at the physiological effect of proline in increasing the quality and productivity of two wheat cultivars grown under saline soil conditions.

2. Materials and methods

2.1 Site and soil description

A two-year field study was carried out during two successive seasons (2023/24 and 2024/25) at a private farm on Tamia, Fayoum Governorate, Egypt latitude 29°30'53.4" N, longitude 30°58'07.8" E, and elevation of -13 m beyond sea level) **Figure 1**. The location is described as hot and dry in summer and cold in winter. Before sowing soil samples were collected to estimate its initial physical and chemical and outputs of soil analysis are presented in **Table 1**.

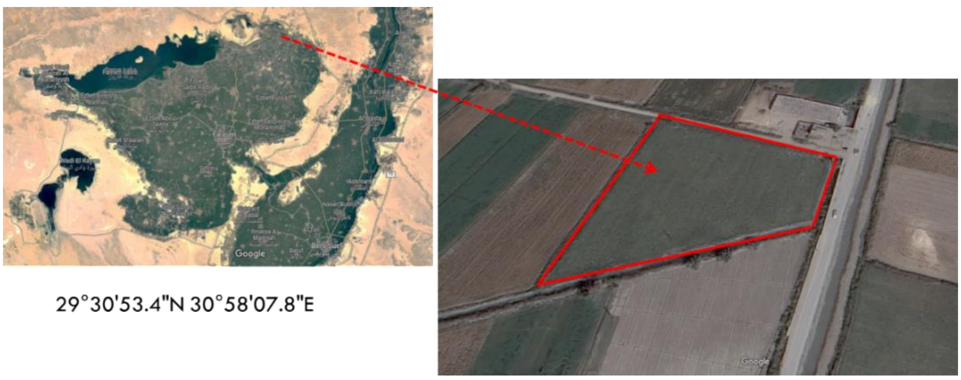

Fig. 1. The field trial site, Tamia, Fayoum Governorate, Egypt; Source: Google Maps.

Table 1. Some Chemical properties of Tamia soil sample.

Ec (ds m^{-1})	TDS (ppm)	pH	Soluble anions (meq L^{-1})				Soluble cantions (meq L^{-1})			
			Co_3^-	Hco_3^-	Cl^-	So_4^{--}	Ca^{++}	Mg^{++}	Na^+	K+
3.82	526	7.60	n.d	1.19	6.43	0.60	1.17	1.41	5.03	0.61
Na (meq 100 g^{-1} soil)		**CEC (meq 100 g^{-1} soil)**		**ESP %**		**GR %**		**GR t ha^{-1} 30 cm depth**		
5.68		30.81		18.45		13.18		12.55		

*CEC (Cation exchange capacity), ESP (exchangeable sodium percentage), GR (Gypsum Requirement).

2.2 Irrigation system description

A traditional surface flood irrigation system was used. Water was sourced directly from an open canal adjacent to the plot using a coastal surface pump. This pump lifted the water from the canal into a distribution sub channel that fed a series of precisely leveled field ditches. From these ditches, water was manually released into individual basins, flooding the wheat plots to a predetermined depth. Before constructing the basins, the entire land was laser-leveled to achieve a uniform slope and perfect surface leveling, which is critical to achieving even water distribution and reducing seepage losses. This method allowed for the controlled application of a known volume of water, facilitating accurate measurement of irrigation input and its impact on crop development, water use efficiency, and soil moisture dynamics within the experimental setup.

2.3 Seasonal irrigation estimation

To calculate the crop water requirements for wheat, meteorological data were recorded throughout two growing seasons in the Tamia region. **Table (2)** summarizes the monthly averages of this climatic data.

The CROPWAT 2012 computer program (version 8.0.1.1) was used to calculate the irrigation values shown in **Table 3**. Using locally gathered meteorological data and the agronomic characteristics of the experimental plants; these values were computed using the FAO Penman-Monteith equation (Allen *et al*., 1998).

$$ET_c = ET_o \times K_c \quad (1)$$

Where

ETc = crop evapotranspiration in mm day^{-1}.

ETo = reference evapotranspiration in mm day^{-1}.

Kc = crop coefficient.

The daily irrigation water requirement for the flood irrigation system was calculated for two seasons using Equation 2 (Allen *et al*., 1998).

$$IR_g = \frac{(ET_o \times k_c)}{E_i} - R + LR \quad (2)$$

Where: IR_g is the crop irrigation requirements, (mm day^{-1}), ET_o is the reference evapotranspiration, (mm day^{-1}), k_c is the crop coefficient **(**Allen *et al*. 2005), E_i is the irrigation efficiency, (%), R is the precipitation, (mm), LR is the leaching requirements, (mm). crop irrigation requirements were converted from mm ha^{-1} day^{-1} to m^3 ha^{-1} day^{-1} (Savva, Frenken, 2002).

Table 2. The monthly averages of the meteorological data (from sowing to harvesting) (2023/24 and 2024/25 seasons) for the Tamia region.

Month	Min Temp (°C)	Max Temp (°C)	Precipitation (mm day^{-1})	Relative Humidity (%)	Wind (Km day^{-1})	Radiation (MJ m^{-2} day^{-1})	ETo (mm day^{-1})
2023/2024							
November	12.5	24.6	0.1	57	220	14.4	3.45
December	10.4	22.1	0.1	63	231	13	2.76
January	7.8	20	0.2	62	219	13.9	2.67
February	5.8	18.8	0.1	63	241	16.2	2.87
March	10.4	25.7	0.1	45	265	22.8	5.17
April	13.1	29.7	0	38	260	27.7	6.8
May	16.9	33.2	0	37	300	29.8	8.29
2024/2025							
November	13.9	25.8	0.3	37	237	20	4.6
December	10.6	21.6	0.1	69	240	17.9	2.77
January	7	19.6	0.9	58	208	13.9	2.67
February	6.9	20.2	0.2	62	212	16.2	2.93
March	9.6	24.5	0.1	53	242	22.8	4.58
April	13.8	30.9	0	43	313	27.7	7.21
May	17.4	34.2	0	34	293	29.8	8.53

Table 3. Irrigation water requirements (m^3 ha^{-1}) for wheat crop (2023/24 and 2024/25 seasons).

Stage	Number of days		Kc	ET_c (mm)		Total of IR (m^3 ha^{-1})	
	1st	2nd		1st	2nd	1st	2nd
Initial	35	32	0.3	2.85	4.15	243	291
Development	45	45	1.15	8.89	7.48	928	777
Mid-season	50	50		21.91	20.61	2106	1977
Late-season	40	40	0.3	22.79	24.34	2167	2357
Total	**170**	**167**				**5444**	**5402**

*ETc = crop evapotranspiration **IR = crop irrigation requirements.

2.4 Experimental design and layout

A split-plot design based on randomized complete block arrangement with three replicates. The main plots were devoted to two wheat varieties (Misr-1 and Misr-3). While, four foliar proline treatments (0 (water as control), 50, 100, and 150 ppm) were allocated at to the sub-plots. Therefore, 8 treatments (cultivars× proline) were distributed in a total of 24 plots (each plot was 15 m^2 with 1.5 m wide bordering portions; the experiment area consists of 20 rows each of 5-meter length and 15 cm between rows). Proline was sprayed twice in the early morning at 30 and 60 days after sowing using a back sprayer. Drops of 0.01% (v/v) Tween 10 were added to the solution to ensure the maximize penetration into the leaves.

2.5 Crop husbandry

Before sowing, the experimental field plowed and meticulously leveled. Fertilizer applications were applies according to recommendations of the Field Crop Research Institute, Agricultural Research Center, Ministry of Agricultural and Land Reclamation, Egypt. Farmyard manure had been deposited at the rate of 20 m^3 $ha^{-1}$and thoroughly mixed with the surface soil layer (0-30 cm) before sowing. Nitrogen (N), phosphorus (P), and potassium (K) fertilizers (150, 90, and 60 kg ha^{-1}) were applied as ammonium sulphate (20.6% N), mono-superphosphate (15.5% P2O5), and potassium sulphate (48% K2O), respectively. A basal dose of 10% N was applied at planting, and the remaining amount was added in four equal doses at 4, 5, 6, and 8 weeks after sowing. Two equal doses of P were added to the soil during soil preparation and at the tillering. Conversely, K applied twice, 4 weeks after sowing and at full bloom. Utilizing the single row manual drill, the grains of wheat were sown in 15 cm rows on November 15, 2023, and November 20, 2024, at the rate of 150 kg seed ha^{-1}. Plants were watered via a traditional surface flood irrigation system.

2.6 Recording data

2.6.1 Growth, pigments and proline

Fifteen plants were chosen at random from each experimental plot 90 days after sowing in order to measure plant height, flag leaf area, number of leaves and shoots dry weight per plant. Photosynthetic pigments i.e. chlorophyll a, chlorophyll b and carotenoid content (mgg^{-1} fresh leaf) were quantified by measuring the absorbance at 645, 663, and 470 nm in a spectrophotometer JASCO V750 (Lichtenthaler and Wellburn, 1983), respectively. Moreover, the free proline content (mg g^{-1} FW) of fresh wheat leaves was estimated, employing the procedures provided by Bates *et al*. (1973).

2.6.2 Yield and yield attributes

In both seasons, harvesting took place during the first week of May. Plant samples were collected from one square meter of each plot. Number of spikes m^{-2} was estimated. Ten tillers were then selected at random to measure the length of the spikes, spikelets number per spike, the grains number per spike, the weight of the grains per spike, and the 1000-grain weight. To assess the grain and straw yields ha^{-1}, the entire plot was harvested.

2.6.3 Irrigation water productivity "IWP"

Biomass and Grain Irrigation Water Productivity "BIWP" and "GIWP" (kg m^{-3}) was calculated as the ratio of biomass and grain yield (kg ha^{-1}) to the total irrigation water applied "TIWA" (m^3 ha^{-1}), for each treatment expressed in kg m^{-3} according to Fernández *et al.* (2020) using the following equations:

$$BIWP\ (kg\ m^{-3}) = \frac{Biomass\ yield\ (kg\ ha^{-1})}{TIWA\ (m^3\ ha^{-1})} \quad (\mathbf{5})$$

$$GIWP\ (kg\ m^{-3}) = \frac{Grain\ yield\ (kg\ ha^{-1})}{TIWA(m^3\ ha^{-1})} \quad (\mathbf{6})$$

2.6.4 Grain chemical analysis

Total carbohydrate percentage in the dry grains was determined using the method given by Herbert *et al*. (1971). The phenol-sulfuric acid technique was used to assess total soluble sugars (Dubois *et al*. 1956). Total N was determined by using micro-kjeldahl method as stated in A.O.A.C. (1970) and total crude proteins computed by multiplying total nitrogen by 5.8.

2.7 Statistical Analysis

Data were statistically analyzed according to Gomez and Gomez (1984), using SAS program software. To differentiate and compare the treatment means at the 0.05 probability level, Duncan's Multiple Range Test (DMRT) was used to separate the treatment means, following the procedure described by Duncan (1955).

3. Results and Discussion

3.1 Wheat growth

3.1.1 Performance of cultivars

As shown in **Table 4**, all values of growth parameters (plant height, flag leaf area and shoot dry weight) for Misr-3 cultivar were greater than those of Misr-1, except no. of leaf in both seasons. The increases in plant height, flag leaf area and shoot dry weight of Misr-3 were 2.76 and 3.65%, 5.53 and 3.87 and 4.31, and 2.86% in the first and second seasons, respectively, over Misr-1. These results may be due to differences in genetic factors between the two tested cultivars. These are in general agreement with those recorded by Ali *et al*. (2007), Hinai *et al.* (2022) Abd El-Rheem *et al*. (2026).

3.1.2 Effect of proline levels

Data provided in **Table 4** reveal substantial increases of all the examined features with increasing proline levels from 0 to 50 and 150 mg L^{-1}. Plant height (cm), flag leaf area (cm^2), shoot dry weight, and number of leaves all significantly increased after 150 mg proline L^{-1} was applied. On contrast, the lowest of aforementioned traits was obtained by untreated plots. As well documented, the salt stress shrink growth and disturbs the physiological status plants, declining the accumulation of assimilates and dry biomass (Mubarak *et al*. 2021). While significant useful effects were observed with the use of proline at a concentration of 100 ppm and 150 ppm on most of the growth traits under study. The simulative impact of vegetative growth, which enhances tillering in cereals and boosts photosynthetic rate, may be the cause of the rise in wheat growth with rising proline levels. Similar results were reported Trovato *et al.* (2008), Abd El-Salam *et al.* (2016) Noreen *et al.* (2018) Abd El-Rheem *et al*. (2026) and Hindi *et al*. (2026).

Table 4. Response of some growth characters of wheat cultivars to spraying with proline levels in 2023/24 and 2024/25 seasons.

Treatments	Plant height (cm)		Flag leaf area (cm^2)		No. of leaves		Shoot dry weight (g)	
	2023/24	2024/25	2023/24	2024/25	2023/24	2024/25	2023/24	2024/25
Cultivars								
Misr-1	106.15b	103.18b	43.93b	42.60b	7.03a	6.78a	13.68b	12.93b
Misr-3	109.08a	106.95a	46.36a	44.25a	7.53a	7.43a	14.27a	13.30a
Proline levels								
0 ppm	100.9c	98.65c	41.03c	40.05d	6.50b	6.50c	12.00c	11.70c
50 ppm	106.20b	103.70b	44.75b	42.75c	7.30a	7.00b	13.35b	12.70b
100 ppm	110.90a	107.75a	46.95a	45.20b	7.55a	7.45ab	15.00a	13.75a
150 ppm	112.45a	110.15a	47.83b	45.70a	7.75a	7.65a	15.53a	14.30a

3.1.3 Interaction effect

Data analysis showed that the interactional effect of wheat cultivars and proline levels had a major impact on flag leaf area and plant height (**Figure 2**). Maximum values of the previous characters were acquired using a combination of Misr-3 cultivar with application of 150 mg proline L^{-1}. On the other hand, Misr-1without proline application gave the lowest values of plant height (cm), flag leaf area of wheat. These findings are consistent with those of Yang *et al.* (2011).

3.2 Photosynthesis pigments and proline

3.2.1 Performance of cultivars

The data of photosynthesis pigments (chlorophyll a, chlorophyll b and carotenoids) in **Table 5** reveal that no significant differences between Misr-3 and Misr-1 cultivars. On the other hand, Misr-3 cultivar gave the maximum values of proline content compared with Misr-1 cultivar. These results are in good harmony with those obtained by Yang *et al.* (2011) and Hinai *et al*. (2022).

3.2.2 Effect of proline levels

Data in **Table 5** revealed that proline treatment resulted in notable increases in photosynthesis pigments and proline content compared to untreated treatment (**Table 5**). The highest chlorophyll a, chlorophyll b, carotenoids and proline content were obtained from plants treated with protine at 150 ppm. On the other hand, the untreated treatment (tap water) produced the lowest values of the preceding characters. These results may be attributed to the involvement of proline in chloroplast defense against oxidative damage (Smirnoff and Cumbes, 1989). Because this amino acid is essential for maintaining membranes and enzymes (Solomon *et al.*, 1994) or increasing the amount of Mg+2 ions required for the synthesis of chlorophyll (Shaddad, 1990). According to Ali *et al.* (2007), proline therapy improves photosynthetic pigments in maize plants by boosting chlorophyll biosynthesis and/or delaying its degradation, improving photosynthetic pigment efficiency, and stabilizing photosynthetic processes. The exogenous application of proline at enhanced the content and efficiency of photosynthetic pigments of wheat plant (Rady and Mohamed, 2018).

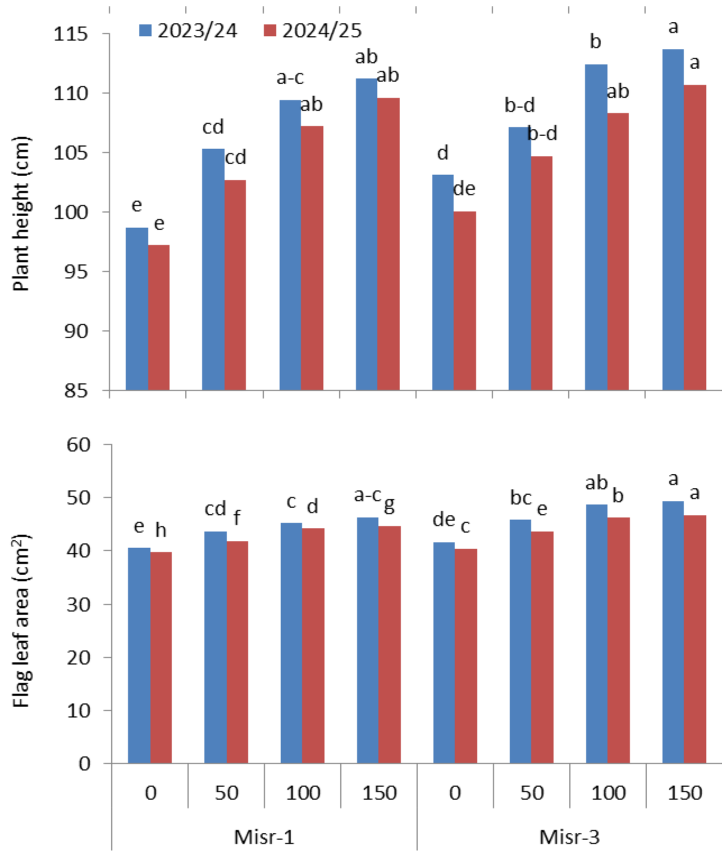

Fig. 2. Response of plant height and flag leaf area of wheat to the interaction between cultivars and spraying with proline levels in 2023/24 and 2024/25 seasons.

Table 5. Response of pigments and proline (mg g[-1] FW) of wheat cultivars spraying with proline levels in 2023/24 and 2024/25 seasons.

Treatments	Chlorophyll a		Chlorophyll b		Carotenoids		Proline	
	2023/24	2024/25	2023/24	2024/25	2023/24	2024/25	2023/24	2024/25
Cultivars								
Misr-1	1.90a	1.91a	0.96a	1.02a	0.96a	1.02a	0.42b	0.52b
Misr-3	1.95a	1.95a	0.99a	1.09a	0.99a	1.09a	0.55a	0.61a
Proline levels								
0 ppm	1.47c	1.43d	0.73c	0.78d	0.73c	0.78d	0.33a	0.38c
50 ppm	1.90b	1.90c	0.92b	1.02c	0.92b	1.02c	0.47b	0.56b
100 ppm	2.12a	2.13b	1.10a	1.18b	1.10a	1.18b	0.54c	0.65a
150 ppm	2.21a	2.28a	1.16a	1.25a	1.16a	1.25a	0.61d	0.68a

3.2.3 Interaction effect

The relationship between proline levels and wheat cultivars has a substantial impact on chlorophyll a, chlorophyll b and protine content (**Figure 3**). The highest chlorophyll a, chlorophyll b and protine content were recorded Misr-3 and proline at 150 ppm treatment. While the lowest number of previous characters was recorded when Misr-1 cultivar was used and untreated treatment. The same results were achieved by EL-Metwally *et al.* (2015) and Dawood *et al.* (2021).

3.3 Yield and yield attributes

3.3.1 Performance of cultivars

The data obtained indicate that Misr-3 cv was characterized by more 1000-grain weight, grain yield, and straw yield than Misr-1 cv as shown in

Table 6. In addition, no significant differences between Misr-3 cv and Misr-1 cv on spike length, grains number spike^{-1}, weight of grains spike^{-1}, number of spikelet's spike^{-1}, number of spikes per m^{2}. Confirming results in this respect were cited by Shaban *et al*. (2019) and Dawood *et al*. (2021).

3.3.2 Effect of proline levels

Data presented in **Table 6** indicate how proline treatments can increase grain production and yield attributes (spike length, grains number spike^{-1}, weight of grains\spike, number of spikelet's spike^{-1}, number of spikes per m^{-2}, straw yield and grains yield). Application of 150 mg proline L^{-1} led to significant increase in previous characters. However, untreated plots produced the lowest of the aforementioned traits. Proline at rate of 150 ppm gave higher values of grain yield ha^{-1}. Such grain output and feed were greatly boosted by treatment over the untreated check by 42.58 and 22.69 % in the initial and subsequent seasons, respectively. These results may be due to the fact that the use of proline increases the ability of plants to tolerate the increased soil salinity and thus enhances the plants' ability to vegetative growth, which in turn is reflected in the yield and its components Dawood *et al.* (2021). Proline application may have increased wheat yield by increasing vegetative growth parameters and photosynthetic pigment, which in turn increased the generation of photosynthetic assimilates that move to the reproductive organs during the maturation and ripening stages. Abd El-Salam *et al.* (2016) and Dawood *et al.* (2021) have validated the beneficial effects of proline spraying on wheat growth and yield components.

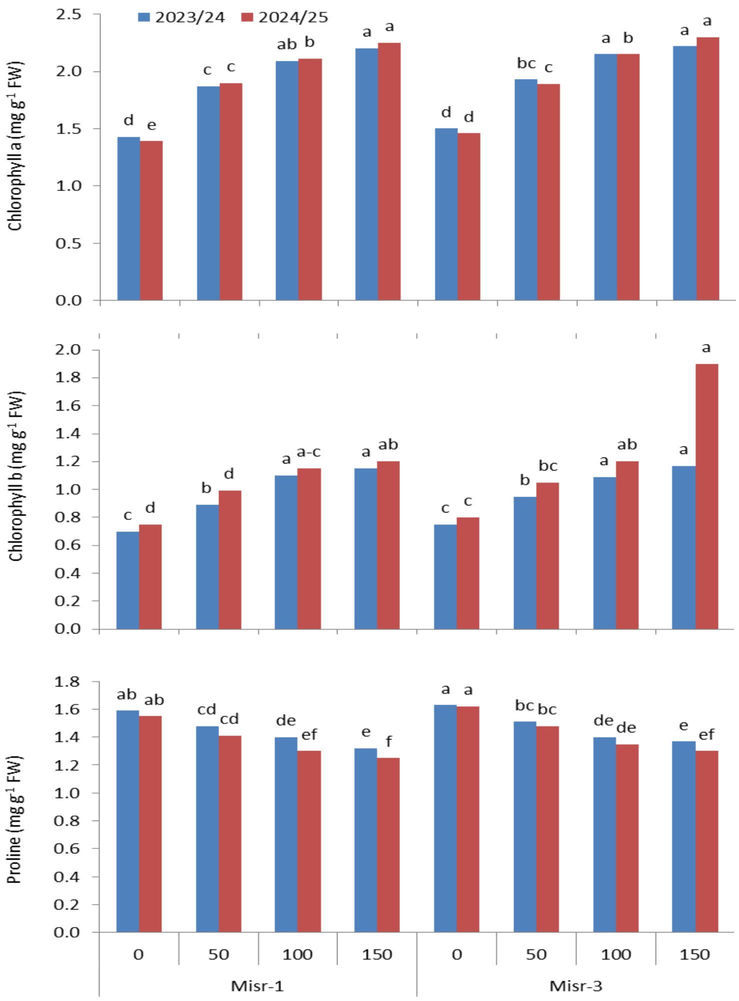

Fig. 3. Response of chlorophyll a, chlorophyllb, and proline content of wheat to the interaction between cultivars and spraying with proline levels in 2023/24 and 2024/25 seasons.

Table 6. Response of yield, yield attributes of wheat cultivars to spraying with proline levels in 2023/24 and 2024/25 seasons.

Treatments	Spikes number m^{-2}	Spike length (cm)	Spikelet's number $spike^{-1}$	Grains number $spike^{-1}$	Grains weight $spike^{-1}$ (g)	1000-grain weight (g)	Straw yield (t ha^{-1})	Grain yield (t ha^{-1})
2023/24								
Cultivars								
Misr-1	361.17a	11.40a	18.08a	57.45a	1.95b	51.81b	7.26b	5..35b
Misr-3	379.58a	12.03a	17.29a	53.59a	2.04a	52.50a	7.56a	5.73a
Proline levels								
0 ppm	314.33d	10.5c	15.00c	49.93d	1.76d	48.00d	6.18d	4.58d
50 ppm	344.50c	11.62b	17.07b	54.83c	1.96c	51.95c	7.26c	5.25c
100 ppm	387.83b	12.25a	18.82ab	57.40b	2.08b	53.62b	7.93b	5.81b
150 ppm	434.83a	12.55a	19.87a	59.92a	2.19a	55.05a	8.26a	6.53a
2024/25								
Cultivars								
Misr-1	353.70a	11.15a	16.88a	53.43a	1.99a	51.98a	5.35b	7.38a
Misr-3	361.28a	11.63a	17.50a	54.88a	2.01a	53.00a	6.43a	7.71a
Proline levels								
0 ppm	310.38b	10.15b	15.00c	49.20c	1.74c	48.35c	4.85c	6.70c
50 ppm	335.52c	11.10ab	16.85b	53.10b	1.98b	52.30b	5.60b	7.30b
100 ppm	380.50b	11.95a	18.40a	56.70a	2.13a	54.25a	6.40a	7.95a
150 ppm	403.55a	12.35a	18.50a	57.60a	2.16a	55.05a	6.70a	8.22a

3.3.3 Interaction effect

Results indicate that Misr-3 cv with 150 mg proline L^{-1} gave the highest number of spikes per m^2, straw yield and grains yield (**Figure 4**). Also, Misr-1 cv produced the lowest values of all the previously listed traits in the absence of proline. These findings are consistent with those of Shaban *et al.* (2019) and Dawood *et al.* (2021).

3.4 Irrigation Water Productivity

3.4.1 Performance of cultivars

Data presented in **Table 7** reveal that Misr-3 cultivar exhibited significantly higher grain IWP and biomass IWP compared to Misr-1 in both seasons. In the first season (2023/24), Misr-3 recorded grain IWP of 1.05 kg m^{-3} and biomass IWP of 2.44 kg m^{-3}, whereas Misr-1 recorded 0.98 and 2.32 kg m^{-3}, respectively. Similarly, in the second season (2024/25), Misr-3 maintained superior water productivity (grain IWP: 1.43 kg m^{-3}; biomass IWP: 2.62 kg m^{-3}) over Misr-1 (1.37 and 2.36 kg m^{-3}).

The superior IWP of Misr-3 can be attributed to its higher grain and straw yields compared to Misr-1, as previously shown in (Table 6). This indicates that Misr-3 utilizes irrigation water more efficiently in producing both economic and biological yields. These results align with (Zhang *et al.*, 2022), who reported that wheat genotypes with higher drought tolerance and yield potential traits tend to exhibit better yield performance under varying water conditions. Furthermore, the better performance of certain wheat cultivars under deficit irrigation in terms of water use efficiency has been documented by (Zhang *et al*., 2023), who found that genotype selection plays a crucial role in improving irrigation water productivity.

3.4.2 Effect of proline levels

The data in (Table 7) demonstrate that foliar application of proline significantly enhanced both grain IWP and biomass IWP in a dose-dependent manner, with the highest values consistently recorded at 150 ppm in both seasons.

In the first season (2023/24), grain IWP increased progressively from 0.84 kg m^{-3} (0 ppm) to 1.20 kg m^{-3} (150 ppm), representing an improvement of approximately 42.9%. Similarly, biomass IWP rose from 1.98 to 2.72 kg m^{-3}, a gain of 37.4% compared to the untreated control. In the second season

(2024/25), similar trends were observed, with grain IWP increasing from 1.24 to 1.52 kg m^{-3} (22.6% increase) and biomass IWP from 2.14 to 2.76 kg m^{-3} (29.0% increase).

The enhancement in IWP due to proline application can be explained by the role of proline as an osmoprotectant and antioxidant. Proline accumulation helps plants maintain cellular hydration, stabilize proteins and membranes, and scavenge reactive oxygen species under water stress conditions (Hadid *et al*., 2023), who reported that foliar spraying of proline at 200–300 mg L^{-1} improved wheat tolerance to drought stress by enhancing photosynthetic pigments and antioxidant enzyme activities, leading to better grain yield and water productivity. Moreover, (Agami *et al*., 2019) demonstrated that proline application significantly increased IWP in wheat plants grown under deficit irrigation, attributed to improved relative water content, chlorophyll content, and antioxidant defense systems. The progressive improvement in IWP with increasing proline concentrations (up to 150 ppm) in the present study suggests that proline mitigates the negative effects of water scarcity, enabling more efficient utilization of irrigation water for both grain and biomass production.

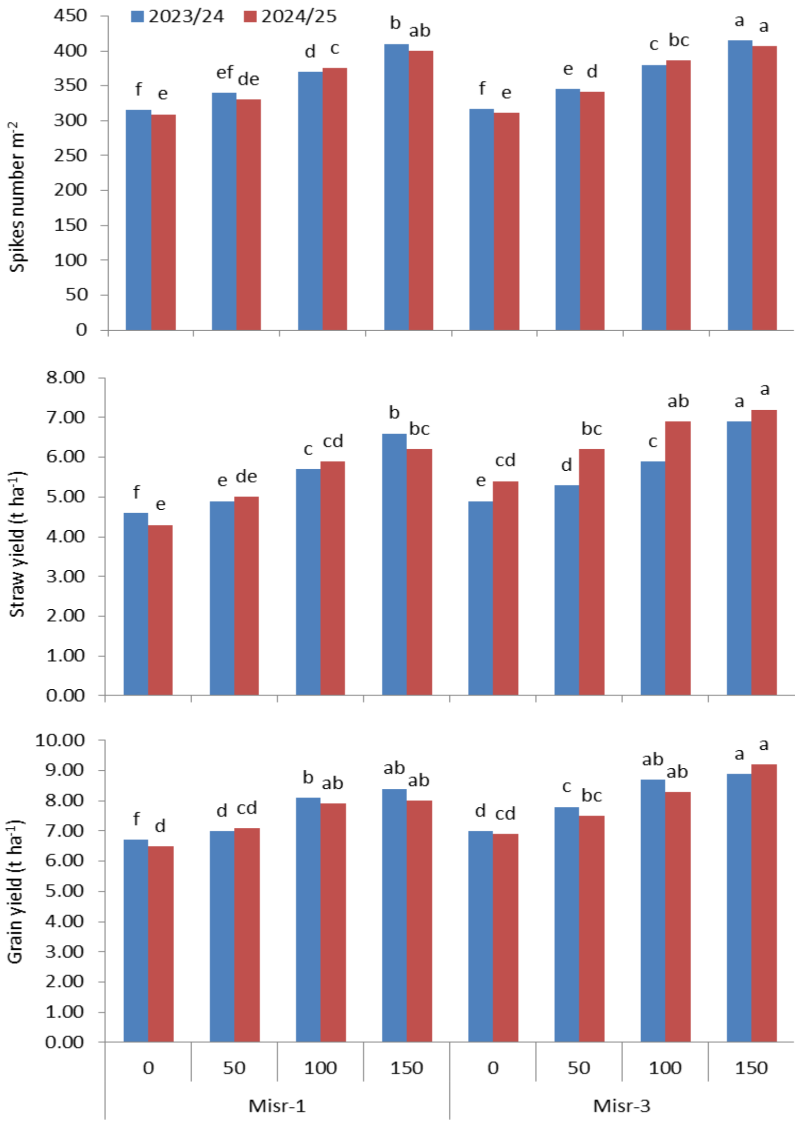

Fig. 4. Response of spikes number m^{-2}, straw yield, and grain yield of wheat to the interaction between cultivars and spraying with proline levels in 2023/24 and 2024/25 seasons.

Table 7. Response of biomass and grain irrigation water productivity of wheat cultivars to spraying with proline levels in 2023/24 and 2024/25 seasons.

Treatments	Straw yield (t ha^{-1})	Grain yield (t ha^{-1})	Total biomass (t ha^{-1})	Biomass irrigation water productivity (kg m^{-3})	Grain irrigation water productivity (kg m^{-3})
2023/24					
Cultivars					
Misr-1	7.26b	5..35b	12.61b	2.32b	0.98b
Misr-3	7.56a	5.73a	13.29a	2.44a	1.05a
Proline levels					
0 ppm	6.18d	4.58d	10.76d	1.98d	0.84d
50 ppm	7.26c	5.25c	12.51c	2.30c	0.96c
100 ppm	7.93b	5.81b	13.74b	2.52b	1.07b
150 ppm	8.26a	6.53a	14.79a	2.72a	1.20a
2024/25					
Cultivars					
Misr-1	5.35b	7.38a	12.73b	2.36b	1.37a
Misr-3	6.43a	7.71a	14.14a	2.62a	1.43a
Proline levels					
0 ppm	4.85c	6.70c	11.55c	2.14c	1.24c
50 ppm	5.60b	7.30b	12.90b	2.39b	1.35b
100 ppm	6.40a	7.95a	14.35a	2.66a	1.47a
150 ppm	6.70a	8.22a	14.92a	2.76a	1.52a

3.4.3 Interaction effect

The interaction between wheat cultivars (Misr-1 and Misr-3) and proline levels (0, 50, 100, and 150 ppm) significantly affected both grain irrigation water productivity (GIWP) and biomass irrigation water productivity (BIWP) in the 2023/24 and 2024/25 seasons, as presented in **Figure 5**.

Grain IWP (GIWP)

In 2023/24, GIWP ranged from 1.19 kg m^{-3} (Misr-1, 50 ppm) to 1.69 kg m^{-3} (Misr-3, 150 ppm). Misr-3 at 100 ppm (1.62 kg m^{-3}) also performed exceptionally, while Misr-1 at 100 and 150 ppm (1.45–1.47 kg m^{-3}) showed moderate improvements. In 2024/25, the highest GIWP was again recorded for Misr-3 at 150 ppm (1.70 kg m^{-3}), followed by Misr-3 at 100 ppm (1.52 kg m^{-3}) and Misr-1 at 100 ppm (1.50 kg m^{-3}). The lowest values (1.30 kg m^{-3}) were observed at 0 and 50 ppm across both cultivars. These results indicate that Misr-3 responded more strongly to proline at 100–150 ppm than Misr-1, reflecting genotypic differences in stress tolerance and water use efficiency (Zhang *et al*., 2022; Hadid *et al*., 2023).

Biomass IWP (BIWP)

For BIWP in 2023/24, the highest values were achieved by Misr-1 at 150 ppm (2.72 kg m^{-3}), Misr-3 at 150 ppm (2.65 kg m^{-3}), and Misr-1 at 100 ppm (2.57 kg m^{-3}). The lowest was Misr-3 at 0 ppm (2.20 kg m^{-3}). In 2024/25, Misr-1 and Misr-3 at 150 ppm both recorded 2.67 kg m^{-3}, while Misr-3 at 0 ppm gave the lowest (2.20 kg m^{-3}). The improvement in BIWP with proline application (up to 150 ppm) confirms that proline enhances total biomass production per unit of water, not only grain yield, which is valuable when straw has economic use (Agami *et al*., 2019; Badr El-Din *et al*., 2022).

In conclusion, the combination of Misr-3 with 100–150 ppm proline consistently produced the highest IWP values across both seasons, making it a promising strategy for improving water productivity in wheat.

3.5 Grain chemical analysis

3.5.1 Performance of cultivars

It was observed that Misr-3 cv had higher soluble sugars, total carbohydrates % and protein % than Misr-1 cv when they were grown under saline soil conditions (**Table 8**). These results may be due to the ability of the Misr-3 variety to tolerate soil salinity more than the Misr-1 variety as well as its increased ability to produce proline and its ability to form and accumulate proline within plants, which increases their ability to tolerate salinity. Shaban *et al*. (2019) and Dawood *et al.* (2021) reported similar findings.

3.5.2 Effect of proline levels

Averages of soluble sugars and total carbs % were considerably impacted by proline levels in both seasons as indicated in **Table 8**. In this regard, the percentage of total carbs and soluble sugars increased gradually with each rise in proline levels.

Therefore, the maximum value of the aforementioned attributes was obtained when proline was applied at a rate of 150 ppm. Vice-versa, the lowest values of the previous characters were reported with untreated plots. Abd El-Salam *et al.*, 2016 reported similar findings.

3.5.3 Interaction effect

The interaction between the two had a substantial impact wheat cultivars and proline levels on total carbohydrates % and protein % (**Figure 6**). The highest total carbohydrates % and protein % was recorded under Misr-3 cv and proline at rate of 150 ppm treatment. While the lowest total carbohydrates % and protein % were recorded when Misr-1 cv was used with untreated plots. Similar results were obtained by Abd El-Salam *et al*. (2016) and Dawood *et al*. (2021).

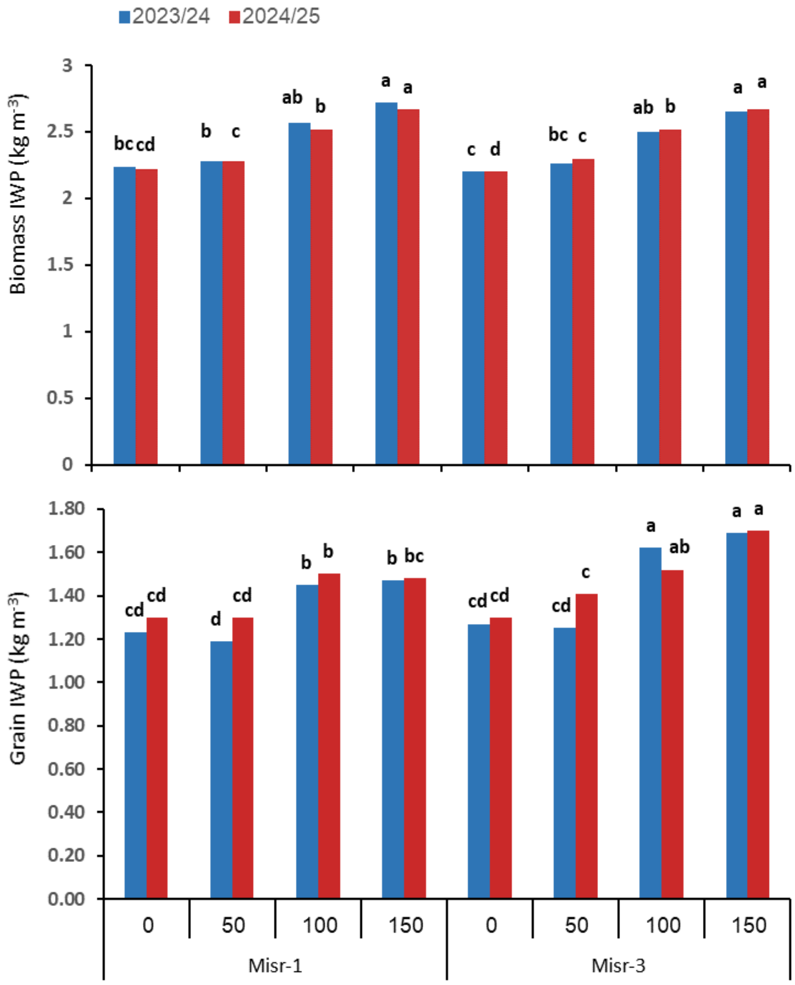

Fig. 5. Response of biomass and grain irrigation water productivity of wheat to the interaction between cultivars and spraying with proline levels in 2023/24 and 2024/25 seasons.

Table 8. Response of chemical composition of wheat cultivars to spraying with proline levels in 2023/24 and 2024/25 seasons.

Treatments	Soluble sugars (mg g^{-1} FW)		Total carbohydrates %		Protein %	
	2023/24	2024/25	2023/24	2024/25	2023/24	2024/25
Cultivars						
Misr-1	20.38b	21.67b	67.30b	67.90b	11.48a	11.20a
Misr-3	21.83a	21.93a	68.33a	68.93a	11.73a	11.55a
Proline levels						
0 ppm	20.40c	21.00b	65.80c	66.55c	11.80c	10.50c
50 ppm	20.75bc	21.40b	67.60b	68.10b	11.40bc	11.20bc
100 ppm	21.15b	21.98ab	68.75a	69.30a	11.90ab	11.75ab
150 ppm	22.10a	22.80a	69.10a	69.70a	12.30a	12.05a

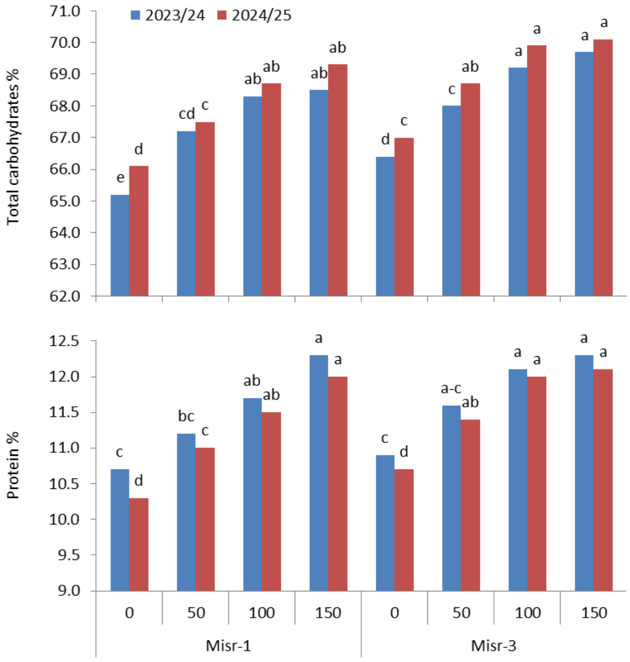

Fig. 6. Response of total carbohydrates and protein of wheat to the interaction between cultivars and spraying with proline levels in 2023/24 and 2024/25 seasons.

Conclusion

In summary, cultivating a suitable wheat variety under saline conditions with exogenous proline application effectively mitigates salinity stress and enhances productivity, water use efficiency, and grain quality. The Misr-3 cultivar outperformed Misr-1 in growth traits, yield attributes, grain and straw yields, as well as grain and biomass irrigation water productivity (IWP). Foliar spraying with proline at 150 ppm produced the highest values for plant height, flag leaf area, photosynthetic pigments (chlorophyll a, b and carotenoids), proline content, yield components, total soluble sugars, carbohydrates %, and protein %. The combination of Misr-3 with 150 ppm proline consistently achieved the highest grain IWP (up to 1.70 kg m^{-3}) and biomass IWP (up to 2.72 kg m^{-3}), indicating more efficient use of irrigation water. Therefore, wheat farmers are advised to cultivate Misr-3 and spray with proline at 150 ppm to obtain high grain yield, high quality, and maximum return per unit of irrigation water under saline soil conditions.

Consent for publication:

All authors declare their consent for publication.

Author contribution:

The manuscript was edited and revised by all authors.

Conflicts of Interest:

The author declares no conflict of interest.

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