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Influence of Irrigation Frequency and Foliar Sprays of Potassium Sulfate and Proline on Maize Performance in Silty Loam Soil

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Abstract: *This experiment was conducted in Kirkuk Governorate in a silty loam soil with the aim of studying the effect of irrigation interval, foliar application of potassium sulfate and proline, and the interaction between these factors on the growth and development of maize plants (Zea mays L.). The experiment included four irrigation intervals (4, 8, 12, and 16 days), and three concentrations of both potassium sulfate (K^+ 41.5%) and proline: (0, 2500, and 5000 mg·L^{-1}) and (0, 100, and 200 mg·L^{-1}), respectively. These treatments were applied as foliar sprays in three replications for each treatment using a randomized complete block design (R.C.B.D). The potassium sulfate and proline sprays were applied 30 days after seed germination, with a second spray 30 days after the first. The results showed that increasing the irrigation interval significantly reduced leaf area, chlorophyll content index, grain potassium content, grain protein content, and grain yield compared to the control treatment (4-day interval). Foliar spraying with potassium sulfate at a concentration of 5000 mg·L^{-1} significantly improved all growth and yield parameters. Spraying with proline at 200 mg·L^{-1} significantly increased leaf area, grain potassium content, and grain protein content. The interaction between the 4-day irrigation interval and potassium sulfate at 5000 mg·L^{-1} led to a significant increase in all studied traits. The combination of 5000 mg·L^{-1} potassium sulfate and 200 mg·L^{-1} proline resulted in significant increases in chlorophyll content index, grain potassium, and protein content. The treatment with a 4-day irrigation interval and 200 mg·L^{-1} proline also significantly increased leaf area, grain potassium, and protein content. Additionally, the interaction between a 4-day irrigation interval and foliar application of 5000 mg·L^{-1} potassium sulfate and 100 mg·L^{-1} proline resulted in a significant increase in leaf area and chlorophyll content index. The combination of a 4-day irrigation interval and foliar application of 5000 mg·L^{-1} potassium sulfate and 200 mg·L^{-1} proline produced the highest values for grain potassium and protein content.*

Keywords: Zea mays L., Irrigation Frequency, potassium sulfate, proline, foliar application.

INTRODUCTION

Maize (*Zea mays* L.) ranks third globally among cereal crops in terms of production, following wheat and rice, reflecting its prominent importance in global markets and food security (Tesfaye *et al.*, 2015). Maize is considered a strategic crop with significant economic and environmental value, as it contributes to farmers 'income, features high productivity, a short life cycle, and the ability to adapt to diverse agricultural environments (Nyirenda *et al.*, 2021). The global agricultural system faces growing challenges, the most significant of which are increasing population pressure—expected to reach 8 billion by 2030—and accelerating climate change, which negatively affects agricultural productivity by causing fluctuations in weather patterns and intensifying extreme climatic events (Lynch, 2019).

Water scarcity is one of the most critical limiting factors for agricultural production in arid and semi-arid regions. This problem is exacerbated by accelerating climate change, which leads to more frequent and severe droughts. Such conditions negatively impact plant growth and reduce agricultural yields globally, ultimately causing a significant decline in agricultural returns (Hafez & Gharib, 2016).

Potassium (K) is a vital element in regulating many physiological processes in higher plants, including maize. It plays a key role in mitigating the effects of water stress by enhancing water-use efficiency, thus reducing the need for frequent irrigation (Ul-Allah *et al.*, 2020). Potassium contributes to efficient stomatal regulation, helps maintain cell turgor, and improves the translocation of sugars from leaves to other parts of the plant, supporting continuous growth even under water stress conditions (Martineau *et al.*, 2017). In addition to its role in fundamental physiological processes, potassium contributes to increasing leaf area, improving nutrient uptake, and enhancing grain weight (Gomaa *et al.*, 2021).

Proline is the most widely used amino acid to reduce losses caused by abiotic stress. Numerous studies have supported the foliar application of proline to increase drought tolerance in maize (Ali *et al.*, 2008) and wheat (Farooq *et al.*, 2017; Farhad *et al.*, 2015). Foliar application of proline mitigates the negative effects of water deficiency on grains by influencing physiological traits (Abdelaal *et al.*, 2020). Proline also moves within cells to supply those needing amino groups for protein synthesis and energy production during drought stress. It is generally non-toxic even at high concentrations, and the oxidation of each proline molecule yields 30 ATP (Behnassi *et al.*, 2011).

This study aims to Evaluate the effect of water stress during different growth stages on maize productivity. Investigate the impact of foliar application of potassium sulfate and its interaction with different irrigation intervals on the morphological and physiological traits of maize. Assess the effect of foliar application of the amino acid proline and its interaction with irrigation intervals on the growth indicators and productivity of maize. Study the interaction between irrigation intervals and foliar application of potassium sulfate and proline on the growth and development of maize plants.

MATERIALS AND METHODS

This experiment was conducted in an agricultural field in Kirkuk Governorate during the fall season of 2023 in a silty loam soil. The objective was to investigate the effect of different irrigation intervals (4, 8, 12, and 16 days) and foliar application of varying concentrations of potassium sulfate and proline—(0, 2500, and 5000 $mg \cdot L^{-1}$) and (0, 100, and 200 $mg \cdot L^{-1}$), respectively—on some morphological and physiological traits of yellow maize (*Zea mays* L.), cultivar "Sajunto". The experiment was designed using a Randomized Complete Block Design (R.C.B.D) (Al-Sahuki & Wahib, 1990) with three replications, arranged in a split plot layout.

The land was plowed using a moldboard plow, leveled, and uniformly fertilized across all experimental units at the time of planting. Fertilization consisted of 200 $kg \cdot ha^{-1}$ of triple superphosphate (P_2O_5 21%) as a phosphorus source (75%), and urea (N 46%) as a nitrogen source (25%). Maize seeds were sown at a spacing of 20 cm between plants and 75 cm between rows, with four rows per plot. All plots were irrigated simultaneously until seed germination was complete. After germination, irrigation was applied according to the specified intervals.

A second dose of urea fertilizer (160 $kg \cdot ha^{-1}$) was applied 25 days after germination. Potassium sulfate (K_2SO_4, K 41.5%) and proline were used as sources of potassium and amino acid, respectively, and were applied in two foliar sprays: the first 30 days after germination, and the second 30 days after the first spray. Manual harvesting was carried out at full maturity on November 10, 2023.

The following parameters were studied: Leaf area, Chlorophyll content index, Grain potassium content, Grain protein content and Grain yield.

Table 1. Some physical and chemical properties of the soil before planting.

Test	Unit of Measurement	Result
Electrical Conductivity	$mc.cm^{-1}$	0.946
pH		7.07

Total Dissolved Solids	$mg \cdot kg^{-1}$	605.604
Total Nitrogen	$mg \cdot kg^{-1}$	980.700
Available Phosphorus	$mg \cdot kg^{-1}$	5.038
Available Potassium	$mg \cdot kg^{-1}$	193.900
Organic Matter	%	1.380
Calcium Carbonate	%	24.770
Clay	%	10
Salt	%	56
Sand	%	34
Texture	Silty Loam	

(Note: Please provide the table if you'd like it translated or formatted.)

STUDIED TRAITS :

1. Leaf Area (cm^2): Leaf area of the leaf located beneath the upper ear (cob) was calculated using the following formula(Elsahookie, 1985):

Leaf Area (cm^2) = Leaf Length × Maximum Width × 0.75

2. Chlorophyll Content Index (CCI): Chlorophyll content index was measured 75 days after planting using a handheld digital SPAD meter 502, directly in the field from the leaf below the upper ear (Felix *et al.*, 2000).

3. Grain Potassium Content (%): Potassium content in grains was measured using a flame photometer according to the method described by Schaffelen *et al.* (1960).

4. Grain Protein Content (%): Protein percentage was calculated using the following formula:

Protein % = Total Nitrogen × 6.25

5. Grain Yield ($g \cdot plant^{-1}$): Grain yield per plant was determined by taking the average grain yield from three plants in each experimental unit. Grains were shelled and weighed using a precision balance.

RESULT AND DISCUSSIONS

Leaf Area (cm^2): Table (2) shows the effects of increasing irrigation intervals and foliar application of different concentrations of potassium sulfate and proline, as well as their interactions, on leaf area. The results revealed a significant decrease in leaf area with increased irrigation intervals. The leaf areas recorded were 683.21, 618.53, and 537.18 cm^2 for irrigation intervals of 8, 12, and 16 days, respectively, compared to 704.61 cm^2 for the control treatment (4-day interval), with percentage reductions of 3.13%, 13.92%, and 22.93%, respectively.

This reduction is attributed to several factors, including changes in leaf morphology, where leaves become smaller and thicker as an adaptation to water scarcity. Additionally, plants tend to close their stomata during drought stress to reduce water loss through transpiration, which in turn affects photosynthesis and thus limits the production of sugars essential for leaf growth and expansion. These findings are consistent with those reported by Wasaya *et al.* (2021) and Chandra *et al.* (2018).

The results presented in Table (2) indicate that foliar application of different concentrations of potassium sulfate had a significant effect on leaf area. Leaf area increased with increasing concentrations, reaching an average of 685.95 cm^2 and 657.25 cm^2 at concentrations of 5000 $mg \cdot L^{-1}$ and 2500 $mg \cdot L^{-1}$ of potassium sulfate, respectively, compared to 591.43 cm^2 at the control concentration (0 $mg \cdot L^{-1}$). The corresponding percentage increases were 11.42% and 11.13%, respectively. This increase is attributed to the role of potassium in enhancing plant tolerance to various stresses such as drought and salinity, which helps maintain leaf area. Additionally, potassium plays a role in increasing photosynthetic efficiency. These results are consistent with the findings of Al-Rawi *et al.* (2023) and Mukhlif *et al.* (2023).

Regarding the effect of different concentrations of proline, a significant variation in leaf area was observed. The highest average leaf area was recorded with 200 $mg \cdot L^{-1}$ of proline at 653.95 cm^2, followed by 100 $mg \cdot L^{-1}$ at 645.57 cm^2, compared to the control (0 $mg \cdot L^{-1}$), which was 635.15 cm^2. The percentage increases were 2.96% and 1.64%, respectively. This is likely due to proline's role in improving plant resistance to water and heat stress, acting as an antioxidant that protects cells from damage caused by free radicals generated under stress. It also contributes to osmotic balance regulation within cells and enhances nutrient absorption necessary for leaf growth. These findings align with those of Priya *et al.* (2019) and Al-Ghanmi *et al.* (2015).

The interaction between irrigation intervals and potassium sulfate concentrations had a significant effect on leaf area. The highest average leaf area was recorded under 4-day irrigation interval with 5000 $mg \cdot L^{-1}$ potassium sulfate, reaching 769.31 cm^2, while the lowest was under 16-day interval with 0 $mg \cdot L^{-1}$ potassium sulfate, at 527.36 cm^2.

Furthermore, the interaction between potassium sulfate and proline concentrations significantly affected leaf area. The combination of 5000 $mg \cdot L^{-1}$ potassium sulfate and 100 $mg \cdot L^{-1}$ proline resulted in the highest average of 714.70 cm^2, whereas the lowest average (569.93 cm^2) was observed with the combination of 0 $mg \cdot L^{-1}$ for both potassium sulfate and proline.

Similarly, the interaction between irrigation intervals and proline concentrations significantly influenced leaf area. The highest average leaf area was recorded at 4-day irrigation and 200 $mg \cdot L^{-1}$ proline, reaching 717.08 cm^2, while the lowest average (563.35 cm^2) was observed under 16-day irrigation with 100 $mg \cdot L^{-1}$ proline. This indicates that irrigation interval has a stronger influence on leaf area than proline concentration alone.

From the three-way interaction among irrigation intervals, potassium sulfate, and proline concentrations, significant differences in leaf area were observed. The highest average (793.79 cm^2) was obtained under 4-day irrigation, 5000 $mg \cdot L^{-1}$ potassium sulfate, and 100 $mg \cdot L^{-1}$ proline, while the lowest average (468.37 cm^2) was recorded under 16-day irrigation with 0 $mg \cdot L^{-1}$ of both potassium sulfate and proline.

Table (2): Effect of irrigation intervals, foliar application of different concentrations of potassium sulfate and proline, and their interactions on leaf area (cm^2).

Irrigation Intervals (days)	Potassium Sulfate $mg.L^{-1}$			Average Irrigation Intervals
	0	2500	5000	
4	629.56 d	714.97 cb	769.31 a	704.61 a
8	636.43 d	690.04 c	723.14 b	683.21 b
12	572.38 e	632.99 d	650.25 d	618.53 c

16	527.36 f	591.04 e	601.13 e	573.18 d

Potassium sulfate ml.L-1	Proline mg.L-1			Average Potassium Sulfate
	0	100	200	
0	569.93 d	582.43 d	621.94 c	591.43 c
2500	668.83 b	639.58 c	663.37 b	657.25 b
5000	666.69 b	714.70 a	676.49 b	685.95 a

Proline mg.L-1	Irrigation Intervals (days)				Average Proline
	4	8	12	16	
0	690.73 abc	666.55 c	609.73 de	573.58 f	635.15 b
100	706.02 ab	698.21 ab	614.70 d	563.35 f	645.57 ab
200	717.08 a	684.85 bc	631.19 d	582.60 ef	653.93 a

Effect of Interaction Between Irrigation Intervals, Potassium Sulfate and Proline				
Irrigation Intervals (days)	Potassium Sulfate mg.L-1	Proline mg.L-1		
		0	100	200
4	0	619.43 h-n	612.77 i-n	656.48 f-j
	2500	718.08 cde	711.51 cde	715.31 cde
	5000	734.68 bcd	793.79 a	779.47 ab
8	0	627.60 g-l	628.12 g-l	653.58 f-k
	2500	687.59 def	718.85 cde	663.68 e-i
	5000	684.47 def	747.67 abc	737.29 bcd
12	0	564.30 n-q	556.12 opq	596.71 k-o
	2500	617.66 i-n	605.97 j-o	675.34 e-h
	5000	647.22 f-k	682.00 d-g	621.52 h-m
16	0	468.37 r	532.72 p-q	590.99 l-p
	2500	652.00 f-k	521.99 q	599.15 j-o
	5000	600.38 j-o	635.34 g-l	567.67 m-q

Chlorophyll Content Index (CCI): The results presented in Table (3) show the effects of different irrigation intervals and foliar application with various concentrations of potassium sulfate and proline, as well as their interactions, on the chlorophyll content index. The findings revealed a significant decrease in CCI as irrigation intervals increased, reaching 41.66, 41.54, and 32.94 at irrigation intervals of 8, 12, and 16 days, respectively, compared to the control treatment of 4 days, which recorded 49.25. This represents a reduction of 18.22%, 18.56%, and 49.51%, respectively. This decline is attributed to water stress, which increases the production of reactive oxygen species (ROS) that can damage chlorophyll molecules. Additionally, drought affects chlorophyll content due to disruption of thylakoid membrane organization and the breakdown of chlorophyll through the activation of proteolytic enzymes. These results are consistent with those reported by Qayyum *et al.* (2021) and Kotb *et al.* (2021).

Furthermore, the results indicate that foliar application with different concentrations of potassium sulfate had a significant effect on CCI, which increased with higher concentrations. The average CCI values were 42.86 and 41.51 at potassium sulfate concentrations of 5000 and 2500 $mg·L^{-1}$, respectively, compared to the control (0 $mg·L^{-1}$), which recorded 39.67. The percentage increases were 8.04% and 4.64%, respectively. This increase in chlorophyll content is likely due to potassium's role in enhancing nutrient uptake, particularly nitrogen, which is a key component of chlorophyll. Similar findings were reported by Li *et al.* (2022) and Wasaya *et al.* (2021). On the other hand, proline concentrations did not show a significant effect on chlorophyll content.

The interaction between irrigation intervals and potassium sulfate concentrations had a significant effect on CCI. The highest CCI was observed at an irrigation interval of 4 days combined with 5000 $mg·L^{-1}$ potassium sulfate, recording 51.17, while the lowest was at an irrigation interval of 16 days and 0 $mg·L^{-1}$ potassium sulfate, recording 32.03.

The interaction between potassium sulfate and proline concentrations also showed a significant effect. The combination of 5000 $mg·L^{-1}$ potassium sulfate and 0 $mg·L^{-1}$ proline recorded the highest CCI of 44.06, which was not significantly different from most other combined treatments except for the treatment with 200 $mg·L^{-1}$ proline and 0 $mg·L^{-1}$ potassium sulfate, which recorded the lowest CCI of 38.02 — a statistically significant difference.

Moreover, the interaction between irrigation intervals and proline concentrations significantly affected CCI. There was a decline in chlorophyll content with increasing irrigation intervals. The highest CCI was recorded at an irrigation interval of 4 days and 100 $mg·L^{-1}$ proline (50.12), while the lowest was at an irrigation interval of 16 days and 100 $mg·L^{-1}$ proline (31.20).

Finally, the three-way interaction among irrigation intervals, potassium sulfate, and proline concentrations significantly affected the chlorophyll content index. The highest CCI was recorded with an irrigation interval of 4 days, 5000 $mg·L^{-1}$ potassium sulfate, and 100 $mg·L^{-1}$ proline, reaching 54.99. The lowest CCI was recorded at 16-day irrigation intervals with 2500 $mg·L^{-1}$ potassium sulfate and 100 $mg·L^{-1}$ proline, reaching 30.38.

Table (3): Effect of irrigation intervals and foliar application with different concentrations of potassium sulfate and proline, and their interactions, on chlorophyll content.

Irrigation Intervals (days)	Potassium Sulfate $mg.L^{-1}$			Average Irrigation Intervals
	0	2500	5000	
4	47.07 ab	49.53 a	51.17 a	49.25 a
8	41.28 cd	40.05 cd	43.65 bc	41.66 b
12	38.31d	43.52 bc	42.79 b-d	41.54 b
16	32.03 e	32.97 e	33.84 e	32.94 c
Potassium sulfate $ml.L^{-1}$	Proline $mg.L^{-1}$			Average Potassium Sulfate
	0	100	200	
0	40.27 ba	40.72 ba	38.02 b	39.67 b

2500	41.17 ba	42.19 ba	41.19 ba	41.51 ab
5000	44.06 a	41.01 ba	43.52 a	42.86 a

Proline mg.L^{-1}	Irrigation Intervals (days)				Average Proline
	4	8	12	16	
0	49.23 a	41.23 b	43.23 b	33.65 c	41.83 a
100	50.41a	42.02 b	41.60 b	31.20 c	41.30 a
200	48.12 a	41.74 b	39.79 b	34.00 c	40.90 a

Effect of Interaction Between Irrigation Intervals, Potassium Sulfate and Proline				
Irrigation Intervals (days)	Potassium Sulfate mg.L^{-1}	Proline mg.L^{-1}		
		0	100	200
4	0	47.83 a-e	46.57 a-e	46.80 a-e
	2500	49.07 a-d	52.94 a	46.57 a-e
	5000	50.80 abc	51.72 ab	50.99 abc
8	0	40.21 d-k	42.82 c-g	40.81 e-j
	2500	40.09 d-k	40.32 e-k	39.74 e-k
	5000	43.38 b-g	42.92 b-h	44.66 a-f
12	0	39.39 e-l	42.15 c-h	33.40 ijkl
	2500	43.68 b-g	43.64 b-g	43.23 b-g
	5000	46.62 a-e	39.02 e-l	42.72 b-h
16	0	33.67 hij	31.35 kl	31.08 kl
	2500	31.85 jkl	31.87 jkl	35.20 g-l
	5000	35.43 i-l	30.38 l	35.71 f-l

Potassium Percentage in Grains: The results presented in Table (4) illustrate the effects of irrigation intervals, foliar application with different concentrations of potassium sulfate and proline, and their interactions on the potassium content in grains. The findings indicate a significant decrease in grain potassium content with longer irrigation intervals, reaching 1.02%, 0.97%, and 0.91% at 8, 12, and 16-day intervals, respectively, compared to the control treatment of 4 days, which recorded 1.05%. This corresponds to reductions of 2.94%, 8.25%, and 15.38%, respectively. This decline is attributed to stomatal closure to reduce water loss through transpiration, which negatively affects photosynthesis and consequently reduces the energy available for nutrient uptake by roots. Additionally, metabolic changes may occur within the plant, affecting the production of organic substances that facilitate potassium transport within plant cells. These findings are consistent with those reported by Abbas *et al.* (2021) and Aqaei *et al.* (2020).

Furthermore, the results indicate that foliar application of potassium sulfate at varying concentrations had a significant effect on increasing the potassium content in grains. The potassium percentages in grains were 1.33% and 0.90% for the concentrations of 5000 and 2500 mg·L^{-1}, respectively, compared to 0.74% in the control (0 mg·L⁻¹). This corresponds to increases of 79.72% and 21.62%, respectively. This improvement is due to the enhanced availability of potassium when applied via foliar spraying, as it is rapidly absorbed by the leaves and increases its concentration in different plant tissues, including the grains. Foliar spraying also overcomes soil-related issues such as potassium fixation or unavailability, and improves potassium transport efficiency within the plant. These findings align with those of Liu *et al.* (2023), Rawal *et al.* (2022), and AL-Bajary & Khalefah (2021).

As for the effect of different concentrations of proline, significant differences were also recorded in grain potassium content. The potassium percentage in grains increased with higher proline concentrations, reaching 1.09% and 0.98% at 200 and 100 mg·L⁻¹, respectively, compared to 0.90% in the control. This corresponds to increases of 21.11% and 8.89%, respectively. This increase is likely due to the role of proline in regulating osmotic pressure and increasing root surface area, which enhances the root's ability to absorb nutrients. These findings agree with Al-Qazzaz (2010) and Al-Hattab (2011).

The interaction between irrigation intervals and potassium sulfate concentrations had a significant effect on grain potassium content. The highest potassium content was observed at the 4-day irrigation interval combined with 5000 mg·L⁻¹ potassium sulfate, recording 1.41%, while the lowest was at the 16-day interval with no potassium sulfate, recording 0.70%.

According to Table (4), the interaction between potassium sulfate and proline concentrations also significantly influenced potassium content in grains. The combination of 5000 mg·L⁻¹ potassium sulfate and 200 mg·L⁻¹ proline produced the highest potassium content (1.47%), whereas the lowest value (0.65%) was recorded at 0 mg·L⁻¹ for both potassium sulfate and proline.

Additionally, the interaction between irrigation intervals and proline concentrations showed that the 4-day interval combined with 200 mg·L⁻¹ proline gave the highest potassium content (1.16%), while the lowest content was recorded at the 16-day interval with 0 mg·L⁻¹ proline, at 0.81%.

The three-way interaction between irrigation intervals, potassium sulfate, and proline concentrations showed significant variation in grain potassium content. The highest value was obtained with a 4-day irrigation interval, 5000 mg·L⁻¹ potassium sulfate, and 200 mg·L⁻¹ proline, reaching 1.51%. The lowest value was observed at a 16-day irrigation interval with 0 mg·L⁻¹ potassium sulfate and proline, recording 0.58%.

Table (4): Effect of irrigation intervals and foliar application of potassium sulfate and proline at different concentrations, and their interactions, on potassium content in seeds.

Irrigation Intervals (days)	Potassium Sulfate $mg.L^{-1}$			Average Irrigation Intervals
	0	2500	5000	
4	0.76 g	0.97 d	1.41 a	1.05 a
8	0.76 g	0.91 e	1.39 a	1.02 b
12	0.72 h	0.88 e	1.32 b	0.97 c
16	0.70 h	0.84 f	0.20 c	0.91 d
Potassium sulfate $ml.L^{-1}$	Proline $mg.L^{-1}$			Average Potassium Sulfate
	0	100	200	
0	0.65 h	0.74 g	0.83 f	0.74 c

2500	0.83 f	0.89 e	0.98 d	0.90 b
5000	1.21 c	1.31 b	1.47 a	1.33 a

Proline mg.L^{-1}	Irrigation Intervals (days)				Average Proline
	4	8	12	16	
0	0.96 d	0.94 de	0.88 f	0.81 g	0.90 c
100	1.03 c	1.01 c	0.96 d	0.91 ef	0.98 b
200	1.16 a	1.11 b	1.08 b	1.02 c	1.09 a

Effect of Interaction Between Irrigation Intervals, Potassium Sulfate and Proline

Irrigation Intervals (days)	Potassium Sulfate mg.L^{-1}	Proline mg.L^{-1}		
		0	100	200
4	0	0.69 no	0.75 lmn	0.84 hi
	2500	0.86 ghi	0.95 f	1.10 e
	5000	1.31 bc	1.38 b	1.51 a
8	0	0.69 no	0.76 k-n	0.84 hij
	2500	0.86 ghi	0.90 fgh	0.97 f
	5000	1.26 c	1.37 b	1.53 a
12	0	0.62 op	0.72 mn	0.82 i-l
	2500	0.83 h-k	0.87 ghi	0.93 fg
	5000	1.17 d	1.29 c	1.49 a
16	0	0.58 p	0.70 m	0.80 i-m
	2500	0.76 j-n	0.83 h-k	0.91 fgh
	5000	1.07 e	1.18 d	1.33 bc

Protein Percentage in Grains: The results presented in Table (5) illustrate the effects of irrigation intervals, foliar application with different concentrations of potassium sulfate and proline, and their interactions on the protein content in grains. The findings indicate a significant decrease in protein content with increased irrigation intervals, recording values of 7.43%, 6.76%, and 5.93% at 8, 12, and 16-day intervals, respectively, compared to 8.16% in the control treatment (4-day interval). These decreases represent reductions of 9.82%, 17.16%, and 37.61%, respectively. This decline is attributed to water stress, which inhibits photosynthesis and thus reduces sugar production—the primary substrate for protein synthesis. Water stress also causes structural changes in enzymes responsible for protein synthesis and redirects the carbon produced from photosynthesis toward vital processes, reducing the carbon available for protein building. These findings contrast with those reported by Javed *et al.* (2022) and De Santis *et al.* (2021).

Additionally, the results show that foliar application of potassium sulfate at varying concentrations significantly increased grain protein content. Protein percentages reached 8.91% and 6.65% at potassium sulfate concentrations of 5000 and 2500 mg·L^{-1}, respectively, compared to 5.64% in the control (0 mg·L⁻¹). These increases correspond to 57.98% and 17.91%, respectively. This improvement is attributed to the role of potassium as an activator of various enzymes involved in protein synthesis and its contribution to the transport of amino acids, the building blocks of proteins, within the plant. These findings align with those of Mirtaleb *et al.* (2021) and Safar-Noori *et al.* (2018).

Regarding the effect of different concentrations of proline, significant differences were also observed in grain protein content. The percentages reached 8.04% and 6.98% at 200 and 100 mg·L⁻¹ of proline, respectively, compared to 6.18% in the control. This represents increases of 30.10% and 12.94%, respectively. This enhancement is due to proline's role in neutralizing reactive oxygen species (ROS) that damage cells and membranes, thereby conserving energy for protein synthesis. Additionally, proline contributes to protein stability and protects against protein degradation under stress. It also influences the expression of genes responsible for stress resistance and protein synthesis. These results agree with those of Hassan & Al-Shaheen (2021) and Fadala & Al-Tahir (2023b).

The results in Table (5) also show that the interaction between irrigation intervals and potassium sulfate concentrations had a significant effect on protein content. The highest protein percentage (10.44%) was recorded at the 4-day irrigation interval with 5000 mg·L⁻¹ potassium sulfate, while the lowest value (4.66%) was observed at the 16-day interval with 0 mg·L⁻¹ potassium sulfate.

A significant interaction effect was also observed between potassium sulfate and proline concentrations. The combination of 5000 mg·L⁻¹ potassium sulfate and 200 mg·L⁻¹ proline produced the highest protein content (11.21%), whereas the lowest value (5.09%) occurred at 0 mg·L⁻¹ for both potassium sulfate and proline.

The interaction between irrigation intervals and proline concentrations also significantly influenced protein content. The highest value (exact percentage not mentioned in the source) was observed at the 4-day interval with 200 mg·L⁻¹ proline, while the lowest protein content (5.25%) was recorded at the 16-day interval with 0 mg·L⁻¹ proline.

The three-way interaction between irrigation intervals, potassium sulfate, and proline concentrations significantly affected protein content. The highest value (13.72%) was observed at the 4-day irrigation interval combined with 5000 mg·L⁻¹ potassium sulfate and 200 mg·L⁻¹ proline, while the lowest protein content (4.07%) was recorded at the 16-day interval with 0 mg·L⁻¹ for both potassium sulfate and proline.

Table (5): Effect of irrigation intervals and foliar application of potassium sulfate and proline at different concentrations, and their interactions, on protein content in seeds.

Irrigation Intervals (days)	Potassium Sulfate mg.L^{-1}			Average Irrigation Intervals
	0	2500	5000	
4	6.64 g	7.41 b	10.44 a	8.16 a
8	5.97 i	6.85 f	9.46 b	7.43 b
12	5.31 j	6.43 h	8.53 c	6.76 c
16	4.66 k	5.91 i	7.22 e	5.93 d
Potassium sulfate ml.L^{-1}	Proline mg.L^{-1}			Average Potassium Sulfate
	0	100	200	

0	5.09 h	5.76 g	6.09 f	5.64 c
2500	6.27 e	6.86 d	6.82 d	6.65 b
5000	7.19 c	8.34 b	11.21 a	8.91 a

Proline mg.L^{-1}	Irrigation Intervals (days)				Average Proline
	4	8	12	16	
0	7.13 e	6.48 g	5.87 i	5.25 j	6.18 c
100	7.88 c	7.22 e	6.73 f	6.11 h	6.98 b
200	9.47 a	8.58 b	7.67.d	6.43 g	8.04 a

Effect of Interaction Between Irrigation Intervals, Potassium Sulfate and Proline

Irrigation Intervals (days)	Potassium Sulfate mg.L^{-1}	Proline mg.L^{-1}		
		0	2500	5000
4	0	6.08 rs	6.77 lmn	7.06 ij
	2500	7.23 hi	7.38 h	7.63 g
	5000	8.08 f	9.51 d	13.72 a
8	0	5.48 u	5.98 st	6.45 op
	2500	6.55 mno	7.03 ijk	6.97 jkl
	5000	7.42 gh	8.64 e	12.32 b
12	0	4.74 w	5.43 u	5.76 p
	2500	5.97 st	6.79 klm	6.53 no
	5000	6.90 jkl	7.98 f	10.70 c
16	0	4.07 x	4.85 vw	5.07 v
	2500	5.32 u	6.26 pqr	6.15 qrs
	5000	6.35 opq	7.22 hi	8.08 f

Grain Yield (g·plant^{-1}): The results shown in Table (6) illustrate the effects of irrigation intervals, foliar spraying with different concentrations of potassium sulfate and proline, and their interactions on grain yield per plant. A significant decrease in grain yield was observed with increasing irrigation intervals. The yield values were 176.32, 138.71, and 123.17 g·plant^{-1} at irrigation intervals of 8, 12, and 16 days, respectively, compared to 204.38 g·plant^{-1} in the control (4-day interval). This represents reductions of 15.91%, 47.34%, and 65.93%, respectively. These reductions are attributed to several factors, such as altered plant growth patterns in response to water stress, reduced leaf area, decreased photosynthesis due to stomatal closure, increased root thickness, and nutrient uptake disturbances. Moreover, higher respiration rates under stress consume more stored energy, ultimately reducing plant productivity. These results align with those reported by Li *et al.* (2022).

Table (6): Effect of irrigation intervals and foliar application of potassium sulfate and proline at different concentrations and their interactions on grain yield per plant.

Irrigation Intervals (days)	Potassium Sulfate mg.L^{-1}			Average Irrigation Intervals
	0	2500	5000	
4	191.45 b	210.62 a	211.09 a	204.38 a
8	168.64 d	182.45 cb	177.88 cd	176.32 b
12	129.02 fg	146.39 e	140.73 e	138.71 c
16	118.58 hi	118.89 h	139.05 ef	123.17 d

Potassium sulfate ml.L^{-1}	Proline mg.L^{-1}			Average Potassium Sulfate
	0	100	200	
0	158.68 bc	146.73 d	150.36 cd	151.92 b
2500	157.88 bc	171.91 a	158.71 bc	162.83 a
5000	167.27 ab	172.36 a	161.93 b	167.19 a

Proline mg.L^{-1}	Irrigation Intervals (days)				Average Proline
	4	8	12	16	
0	200.13 b	188.40 c	129.65 f	126.96 fg	161.28 ab
100	215.71 a	169.51 d	143.35 e	126.10 fg	163.67 a
200	197.32 cb	171.07 d	143.147 e	116.46 g	157.00 b

Effect of Interaction Between Irrigation Intervals, Potassium Sulfate and Proline

Irrigation Intervals (days)	Potassium Sulfate mg.L^{-1}	Proline mg.L^{-1}		
		0	100	200
4	0	218.22 abc	182.03 e-h	175.00 f-j
	2500	176.53 f-j	235.67 a	219.66 ab
	5000	205.63 bcd	229.43 a	198.21 cde
8	0	172.97 f-i	167.71 g-k	165.25 g-l
	2500	200.26 b-e	184.85 d-g	162.23 h-m
	5000	191.94 def	155.96 i-l	185.73 d-g
12	0	124.98 p-s	121.01 q-t	141.08 k-p
	2500	136.79 n-s	151.71 j-n	150.67 k-n
	5000	127.18 o-s	157.32 i-n	137.69 n-r
16	0	118.56 rst	116.17 rst	121.01 q-t
	2500	117.96 rst	115.40 st	102.30 t
	5000	144.35 l-p	146.74 k-o	126.08 o-s

Regarding the foliar application of potassium sulfate, a significant increase in grain yield was observed with higher concentrations. Yields reached 167.19 and 162.83 g·plant^{-1} at concentrations of 5000 and 2500 mg·L^{-1}, respectively, compared to 151.92 g·plant^{-1} for the control (0 mg·L^{-1}), corresponding to increases of 10.05% and 7.18%, respectively. This improvement is attributed to potassium's role in enhancing photosynthesis (via regulation of stomatal movement), sugar translocation to grains, starch and protein synthesis, and increasing resistance to water stress, diseases, and pests. These findings are consistent with Qu *et al.* (2024) and Khokhar *et al.* (2022).

In contrast, the results showed no significant effect of proline concentrations on grain yield per plant. This contradicts findings from Badawi *et al.* (2023) and Fadala & Al-Tahir (2023a), which reported positive effects.

The results presented in the table showed a significant variation in the mean grain yield per plant due to the interaction between irrigation intervals and foliar application of different concentrations of potassium sulfate. The highest mean yield was recorded at the 4-day irrigation interval with the application of 5000 mg·L⁻¹ potassium sulfate, reaching 211.09 g·plant⁻¹, while the lowest mean was observed at the 16-day irrigation interval with 2500 mg·L⁻¹ potassium sulfate, recording 111.89 g·plant⁻¹.

The two-way interaction between potassium sulfate and proline concentrations also had a significant effect on grain yield. The highest mean was obtained from the treatment with 5000 mg·L⁻¹ potassium sulfate and 100 mg·L⁻¹ proline, reaching 172.36 g·plant⁻¹, whereas the lowest yield was recorded for the treatment with 100 mg·L⁻¹ proline and 0 mg·L⁻¹ potassium sulfate, which was 146.37 g·plant⁻¹.

The interaction between irrigation intervals and proline concentrations also had a significant impact on grain yield. The highest yield was recorded with irrigation every 4 days and foliar application of 100 mg·L⁻¹ proline, reaching 215.71 g·plant⁻¹, while the lowest yield was observed with irrigation every 16 days and 200 mg·L⁻¹ proline, which was 116.46 g·plant⁻¹. This indicates that irrigation frequency has a more pronounced effect on grain yield than proline concentration.

The three-way interaction between irrigation intervals and foliar application of different concentrations of potassium sulfate and proline resulted in significant differences. The highest mean yield was recorded with irrigation every 4 days, 2500 mg·L⁻¹ potassium sulfate, and 100 mg·L⁻¹ proline, reaching 235.67 g·plant⁻¹. In contrast, the lowest yield was recorded with irrigation every 16 days, 2500 mg·L⁻¹ potassium sulfate, and 200 mg·L⁻¹ proline, reaching 102.30 g·plant⁻¹.

CONCLUSION:

The study demonstrates that extending the irrigation interval negatively affects plant growth and yield-related parameters. However, foliar application of potassium sulfate at 5000 mg·L⁻¹ and proline at 200 mg·L⁻¹ individually and in combination significantly enhances plant performance. The most notable improvements in leaf area, chlorophyll content index, grain potassium, and protein content were observed when these treatments were applied under the optimal irrigation interval (4-day). To achieve optimal growth and grain quality, it is recommended to maintain a 4-day irrigation interval and apply foliar sprays of potassium sulfate at 5000 mg·L⁻¹ combined with proline at 200 mg·L⁻¹. This combination maximizes key physiological and yield-related traits, thereby enhancing crop productivity.

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