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Potential Effect of Mycorrhizal Inoculation, Fulvic Acid and Potassium Silicate on the Activity of Enzymatic Antioxidants and Nutritional Status of Wheat Grown Under Drought Conditions

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ABSTRACT

Given the importance of wheat as a strategic crop and the increasing threats posed by water scarcity, this study aims to evaluate the effects of mycorrhizal inoculation, fulvic acid and potassium silicate on the activity of enzymatic antioxidants in leaves of wheat and nutritional status of grain under skipping different irrigation. The experiment followed a split-split plot design, as the main factor was the irrigation treatments [I_1: 5 irrigations were done, I_2:3 irrigations were done and I_3:2 irrigations were done]. The sub-main factor was the mycorrhizal [M_1: without mycorrhizal and M_2: With mycorrhizal]. The sub-submain factor was the foliar spray treatments [F_1: without spraying, F_2: Fulvic acid, F_3: Potassium silicate and F_4: fulvic acid + potassium silicate]. The highest levels of POD, CAT, SOD and MDA were recorded under severe water stress (I_3), while the lowest values were observed under traditional irrigation (I_1). The mycorrhizal (M_2) significantly reduced oxidative stress in the plants compared to the control (M_1). The combination of fulvic acid and potassium silicate (F_4) resulted in the lowest enzymatic antioxidant activity and MDA levels. The traditional irrigation (I_1) resulted in the highest NPK, carbohydrate and protein values in grains, while skipping irrigation events (I_2 and I_3) led to a significant reduction in these criteria. Additionally, M_2 treatment led to higher NPK, carbohydrate and protein values compared to the control (M_1). The foliar application of fulvic acid and potassium silicate, especially when combined (F_4), further improved nutrient content and quality traits compared to untreated plants.

Keywords: Wheat, drought, mycorrhiza, fulvic, potassium

INTRODUCTION

Water scarcity is one of the most pressing challenges facing global agriculture (Mahato *et al.* 2022), significantly affecting the productivity of staple crops (Shemer *et al.* 2023). Wheat (*Triticum aestivum* L.), as one of the world's most important cereal crops, is particularly vulnerable to water stress (Afzal *et al.* 2015). It serves as a primary food source for billions of people, contributing substantially to global food security and economic stability (El Sabagh *et al.* 2019). The demand for wheat continues to rise due to population growth and increasing consumption, necessitating sustainable strategies to enhance its resilience under water-deficient conditions (Hossain *et al.* 2021). Beyond its economic importance, wheat is highly valued for its nutritional content, providing essential carbohydrates, proteins, vitamins, and minerals, making it a crucial component of human diets worldwide (Sharma *et al.* 2022).

To mitigate the adverse effects of water stress on wheat, biological soil amendments such as *arbuscular mycorrhizal fungi* (AMF) have gained increasing attention (Mathur *et al.* 2019). Mycorrihizal establish symbiotic relationships with plant roots, enhancing water and nutrient uptake, particularly phosphorus, which plays a vital role in plant metabolism and root development (Metwally *et al.* 2019). Additionally, AMF improves plant drought tolerance by stimulating antioxidant defense systems and promoting osmotic adjustment (Abdelaal *et al.* 2024), thereby increasing wheat's ability to withstand prolonged periods of water deficiency (Tang *et al.* 2022).

Another promising strategy to improve wheat resilience under drought conditions is the application of fulvic acid (Pourmorad *et al.* (2018), a naturally occurring organic compound derived from humic substances (Yang *et al.* 2019). Foliar application of fulvic acid plays a crucial role in enhancing plant growth and stress tolerance (Hamed *et al.* (2021). As a low-molecular-weight organic compound, fulvic acid is easily absorbed by plant leaves, facilitating the rapid uptake of essential nutrients such as nitrogen, phosphorus and potassium (Rafie *et al.* 2021). It improves photosynthetic efficiency, enhances enzyme activity, and stimulates root development, even when applied to the foliage (Faluku *et al* 2024). Additionally, fulvic acid acts as a natural bio-stimulant, promoting cell division, delaying senescence, and increasing chlorophyll content (Zhu *et al.* 2024). Under drought conditions, foliar spraying with fulvic acid helps plants maintain water balance by improving stomatal regulation and reducing oxidative stress, thereby enhancing overall plant resilience and productivity (Chen *et al.* 2025).

Similarly, silicon-based compounds, particularly potassium silicate (K_2SiO_3), have been widely recognized for their role in strengthening plant defense mechanisms against abiotic stress (Gomaa *et al.*2021). Silicon accumulation in plant tissues enhances cell wall integrity, reduces transpiration losses, and improves water-use

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efficiency (Abdelaziz *et al.* 2023). Additionally, potassium silicate has been shown to activate stress-related biochemical pathways, enhancing the plant's antioxidant response and minimizing oxidative damage caused by drought stress (Karvar *et al.* 2023). The protective effects of silicon application make it a valuable tool in improving wheat growth and yield under challenging environmental conditions (Saudy *et al.* 2023).

Given the importance of wheat as a strategic crop and the increasing threats posed by water scarcity, this study aims to evaluate the combined effects of mycorrhizal inoculation, fulvic acid, and potassium silicate on the activity of enzymatic antioxidants and nutritional status of wheat grown under different irrigation regimes. By integrating these approaches, this research seeks to identify effective agronomic practices that enhance wheat resilience to water stress, ensuring sustainable production and food security in arid and semi-arid regions.

MATERIALS AND METHODS

A field experiment was conducted in Ezbet Abu Shaer, Sherbin District, Dakahlia Governorate, Egypt, during the 2022/23 and 2023/24 growing seasons. Before sowing, soil samples were collected and analyzed as described by Tandon, (2005) for their physical and chemical properties to assess soil conditions. The Characteristics of the experimental soil are shown in Table 1.

Table 1. Characteristics of the experimental soil before sowing (combined data over both seasons)

Properties		Values
- The initial soil analyses were dos as described by Tandon, (2005)		
- The samples were taken at depth of 30 cm		
Particle size distribution (%)		
Textural class is Clay	sand,%	22.0
	Silt,%	28.0
	Clay,%	50.0
Chemical measurements and analyses		
Organic matter, %		1.23
pH		8.10
EC dSm^{-1}		2.15
Organic matter, %		1.0
Available phosphorus, $mgKg^{-1}$		8.39
Available nitrogen, $mgKg^{-1}$		45.5
Available potassium, $mgKg^{-1}$		230.5

The wheat cultivar used in this study was Sakha 95, which is well-adapted to various environmental conditions. The wheat cultivar was obtained from the ministry of agricultural and soil reclamation (MASR). The experiment followed a split-split plot arrangement in Randomized Complete Block Design (RCBD) with three replications, including the following factors.

The main factor was the irrigation treatments and Fig 1 shows the flowchart of irrigation treatments, as follows:

I_1: Traditional irrigation (5 irrigations were done)
I_2: Skipping two irrigations (3 irrigations were done)
I_3: Skipping three irrigations (2 irrigations were done)

The sub-main factor was the mycorrhizal treatments as follows;

M_1: Control (without mycorrhizal)
M_2: With mycorrhizal application before sowing.

The sub-main factor was the foliar spray treatments as follows;

F_1: Control (without spraying)
F_2: Fulvic acid (FA) at rate of 1.0 kg/feddan
F_3: Potassium silicate (K_2SiO_3) at rate of 1.0 kg/feddan
F_4: Combination of fulvic acid and potassium silicate at the same rates.

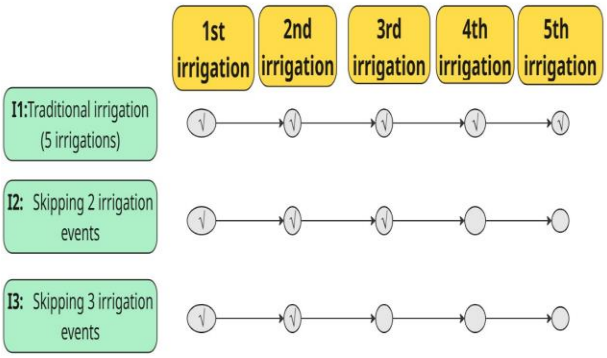

Fig1. Flowchart of irrigation treatments

Wheat seeds were sown on November 15 in both seasons using the Afir sowing method with the curtain technique, ensuring uniform seed distribution at an appropriate depth. The seeding rate was 50 kg/feddan to achieve optimal plant density. Nitrogen fertilizer was applied at a rate of 150 kg urea/feddan, split into two equal doses. Potassium sulphate at a rate of 50 kg/feddan was applied during soil preparation. Calcium superphosphate at a rate of 200 kg/feddan was incorporated into the soil before sowing to ensure phosphorus availability during early. In this experiment, mycorrhizal was applied directly with the seeds at sowing to ensure optimal root colonization and early symbiotic establishment. The mycorrhizal inoculum was mixed with the wheat seeds before planting, allowing the spores to come into direct contact with the emerging roots. This method enhances the efficiency of mycorrhizal colonization, promoting better nutrient uptake, particularly phosphorus, and improving plant water absorption. The incorporation of mycorrhizal at sowing is an effective strategy to support wheat growth under abiotic stress conditions, contributing to enhanced drought tolerance, root development, and overall crop productivity.

Foliar spraying treatments were applied three times: the first spray was conducted 45 days after sowing, followed by two additional sprays at 10-day intervals. The fulvic acid and potassium silicate used in this experiment were purchased from the Egyptian commercial market. Fulvic acid was applied as an organic growth stimulant to improve nutrient absorption and stress tolerance. Potassium silicate was used as a protective agent to enhance plant resistance to abiotic stresses, particularly drought and heat stress. Both substances were applied at a rate of 1.0 kg per feddan to evaluate their individual and combined effects on wheat growth and yield. The wheat crop was harvested at full maturity to ensure optimal grain yield and quality.

Harvesting was carried out manually using sickles to minimize grain losses and ensure accurate yield measurement. The plants were cut close to the ground and left in the field for a short period to dry before threshing. After threshing, the grains were cleaned and weighed to determine the final yield per feddan. In addition to grain yield, other yield components such as straw weight and harvest index were recorded to evaluate the overall productivity of the different treatments. Table 2 shows all the studied traits at two stages (booting and harvest), using nine randomly selected plants for each treatment. Data were statistically analyzed using Costat software, and mean comparisons were performed using LSD at 5% to determine the significance of differences among treatments as described by Gomez and Gomez (1984).

Table 2. Methods, formula and references of measurements

Measurements		Methods and formula	References
	Booting stage		
Enzymes	Polyphenol oxidase (PPO, unit mg^{-1} protein^{-1}) Catalase (CAT, unit mg^{-1} protein^{-1}) Superoxide (SOD, unit mg^{-1} protein^{-1})	Spectrophotometrically	Alici and Arabaci, (2016)
Oxidation indicators	Malondialdehyde (MDA, µmol. g^{-1})	Spectrophotometrically	Davey *et al.* (2005)
	Harvest stage		
Digesting the wheat grain	Digesting was done using mixed of H_2SO_4+ $HClO_4$		Peterburgski, (1968)
Grain chemical constitutes	N, P, K (%)	Micro-Kjeldahl apparatus, spectrophotometric apparatus and flame photometer apparatus, respectively	Walinga *et al.* (2013)
Quality of grain	Carbohydrate and protein (%)		A.O.A.C (2007)

RESULTS AND DISCUSSIONS

1.Enzymatic antioxidants and malondialdehyde (MDA) as a lipid peroxidation marker

The oxidative stress response in wheat plants was assessed by measuring the activity of enzymatic antioxidants, including peroxidase (POD), catalase (CAT) and superoxide dismutase (SOD), along with malondialdehyde (MDA) levels as a lipid peroxidation marker. The data of Table 3 indicate significant variations in these parameters due to irrigation treatments, mycorrhizal application and foliar treatments.

Table 3. Effect of skipping irrigation events, mycorrhizal, fulvic acid and potassium silicate on oxidation indicators in leaves of wheat plants after 70 days from sowing during seasons of 2022/23 and 2023/24

Parameters			POD, unit g^{-1} protein^{-1}		CAT, unit g^{-1} protein^{-1}	
Treatments			1stseason	2ndseason	1stseason	2ndseason
Main factor: Irrigation treatments						
I_1: Traditional irrigation (5 irrigations)			0.95c	0.98a	40.12c	41.38c
I_2: Skipping 2 irrigations			1.01b	1.05a	41.81b	43.30b
I_3: Skipping 3 irrigations			1.22a	1.26a	47.87a	49.54a
LSD at 5%			0.01	NS*	0.16	0.45
Sub factor: Mycorrhizal treatments						
M_1: Control (Without mycorrhizal)			1.12a	1.16a	45.07a	46.62a
M_2: With mycorrhizal			1.00b	1.03b	41.45b	42.86b
LSD at 5%			0.01	0.01	0.16	0.38
Sub-sub factor: Foliar treatments						
F_1: Control (without spraying)			1.08a	1.12a	43.81a	45.28a
F_2: Fulvic acid (FA)			1.07b	1.11b	43.54ab	44.91b
F_3: Potassium silicate (K_2SiO_3)			1.04c	1.08c	43.28b	44.80b
F_4: FA+ K_2SiO_3			1.04c	1.08c	42.42c	43.97c
LSD at 5%			0.01	0.01	0.38	0.35
Interaction						
I_1	M_1	F_1	1.08	1.11	44.11	45.42
		F_2	1.07	1.10	43.37	44.60
		F_3	0.93	0.97	43.30	44.85
		F_4	0.93	0.96	39.47	40.91
	M_2	F_1	0.88	0.90	38.13	39.22
		F_2	0.88	0.90	37.86	38.87
		F_3	0.87	0.90	37.65	38.84
		F_4	0.96	1.00	37.06	38.32
I_2	M_1	F_1	1.15	1.19	45.18	46.69
		F_2	1.14	1.17	44.71	46.05
		F_3	1.10	1.15	44.19	45.87
		F_4	1.09	1.13	44.13	45.85
	M_2	F_1	0.92	0.96	39.37	40.81
		F_2	0.91	0.94	39.25	40.50
		F_3	0.90	0.94	39.05	40.57
		F_4	0.89	0.92	38.57	40.04
I_3	M_1	F_1	1.26	1.31	48.20	49.97
		F_2	1.26	1.30	48.20	49.91
		F_3	1.24	1.29	48.04	49.70
		F_4	1.23	1.27	48.00	49.58
	M_2	F_1	1.22	1.26	47.86	49.57
		F_2	1.19	1.23	47.87	49.50
		F_3	1.17	1.22	47.45	48.96
		F_4	1.16	1.21	47.30	49.13
LSD at 5%			0.02	0.02	0.95	0.86

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
NS*=Non-significant

Table 3. Continued

Treatments			SOD, unit g^{-1} protein^{-1} 1stseason	SOD, unit g^{-1} protein^{-1} 2ndseason	MDA, µmol g^{-1} F.W 1stseason	MDA, µmol g^{-1} F.W 2ndseason
Main factor: Irrigation treatments						
I_1: Traditional irrigation (5 irrigations)			6.20c	5.72c	11.44c	10.56c
I_2: Skipping 2 irrigations			6.61b	6.10b	12.45b	11.48b
I_3: Skipping 3 irrigations			7.54a	6.95a	14.81a	13.67a
LSD at 5%			0.12	0.07	0.14	0.11
Sub factor: Mycorrhizal treatments						
M_1: Control (Without mycorrhizal)			7.09a	6.53a	13.63a	12.57a
M_2: With mycorrhizal			6.47b	5.98b	12.16b	11.23b
LSD at 5%			0.12	0.05	0.11	0.10
Sub-sub factor: Foliar treatments						
F_1: Control (without spraying)			6.90a	6.36a	13.20a	12.20a
F_2: Fulvic acid (FA)			6.83ab	6.31ab	12.96ab	11.97b
F_3: Potassium silicate (K_2SiO_3)			6.74bc	6.22bc	12.82bc	11.80bc
F_4: FA+ K_2SiO_3			6.65c	6.13c	12.61c	11.63c
LSD at 5%			0.12	0.12	0.25	0.23
Interaction						
I_1	M_1	F_1	6.71	6.19	12.75	11.77
		F_2	6.63	6.12	12.32	11.37
		F_3	6.41	5.90	11.94	10.97
		F_4	6.32	5.82	11.88	10.96
	M_2	F_1	6.02	5.56	10.85	10.07
		F_2	5.88	5.46	10.74	9.93
		F_3	5.85	5.41	10.60	9.77
		F_4	5.77	5.30	10.42	9.62
I_2	M_1	F_1	7.19	6.64	13.83	12.74
		F_2	7.14	6.58	13.43	12.41
		F_3	7.05	6.52	13.38	12.33
		F_4	6.87	6.34	13.14	12.10
	M_2	F_1	6.21	5.71	11.70	10.79
		F_2	6.17	5.69	11.51	10.64
		F_3	6.13	5.67	11.52	10.60
		F_4	6.09	5.62	11.06	10.19
I_3	M_1	F_1	7.79	7.16	15.43	14.25
		F_2	7.73	7.13	15.37	14.14
		F_3	7.65	7.04	15.16	13.96
		F_4	7.58	6.96	14.98	13.83
	M_2	F_1	7.49	6.91	14.65	13.59
		F_2	7.42	6.88	14.42	13.35
		F_3	7.34	6.80	14.29	13.18
		F_4	7.29	6.71	14.16	13.06
LSD at 5%			0.29	0.29	0.60	0.55

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
NS*=Non-significant

Skipping irrigation events significantly influenced antioxidant enzyme activity and MDA accumulation. The highest levels of POD, CAT, and SOD were recorded under severe water stress (I_3: skipping 3 irrigation events), while the lowest values were observed under traditional irrigation (I_1: five irrigations). Similarly, MDA levels increased significantly with increased water stress, indicating enhanced lipid peroxidation and oxidative damage under drought conditions.

The application of mycorrhizal (M_2) significantly reduced oxidative stress in wheat plants compared to the control (M_1). Mycorrhizal-treated plants exhibited lower POD, CAT, and SOD activities alongside reduced MDA content, suggesting that mycorrhizal helped mitigate oxidative stress and enhance plant resilience under water-deficit conditions. Foliar applications significantly influenced antioxidant enzyme activity and MDA accumulation. The combination of fulvic acid and potassium silicate (F_4) resulted in the lowest enzymatic antioxidant activity and MDA levels, indicating reduced oxidative stress. In contrast, untreated plants (F_1) showed the highest levels, suggesting that foliar treatments alleviated oxidative damage.

The interaction between irrigation, mycorrhizal, and foliar treatments further highlighted the role of these factors in stress mitigation. Under severe drought (I_3), mycorrhizal-treated plants with fulvic acid and potassium silicate (M_2F_4) exhibited the lowest MDA content, demonstrating an improved oxidative stress response. The observed increase in antioxidant enzyme activity (POD, CAT, and SOD) under reduced irrigation regimes indicates an adaptive response of wheat plants to oxidative stress caused by water deficit (Bashir *et al.* 2016; Tari, 2016). Drought stress leads to excessive production of reactive oxygen species (ROS), such as superoxide radicals (O_2^-) and hydrogen peroxide (H_2O_2), which cause oxidative damage to cellular membranes, as evidenced by the elevated malondialdehyde (MDA) content (Zhou *et al.* 2021; Li *et al.* 2022). The application of mycorrhizal inoculation (M_2) mitigated these effects by enhancing water and nutrient uptake, particularly phosphorus, and by stimulating the production of natural antioxidants that scavenge ROS, resulting in lower MDA levels and reduced oxidative damage (Mathur *et al.* 2019; Metwally *et al.* 2019;Abdelaal *et al.* 2024).Additionally, foliar application of fulvic acid (FA) and potassium silicate (K_2SiO_3) further alleviated oxidative stress by strengthening cell walls, improving water retention, and enhancing enzymatic and non-enzymatic antioxidant defense mechanisms (Saudy *et al.* 2023; Faluku *et al.* 2024). The combined treatment of mycorrhizal with foliar application of

FA and K_2SiO_3 showed the most significant reduction in oxidative stress markers, highlighting their synergistic role in improving wheat resilience under drought conditions.

2. Grain quality

Table 4 shows the effects of different irrigation regimes, mycorrhizal inoculation, and foliar treatments on the chemical composition of wheat grains after harvest during the 2022/23 and 2023/24 seasons. The measured parameters include nitrogen (N), phosphorus (P) and potassium (K) concentrations. The results show a significant impact of water stress, mycorrhizal, and foliar treatments on grain mineral content.

Table 5 evaluates the same experimental treatments but focuses on the biochemical traits of wheat grains, specifically carbohydrate and protein content. These traits are crucial indicators of wheat grain quality and nutritional value. The data indicate significant variations due to irrigation levels, mycorrhizal inoculation, and foliar application.

From Table 4, it is evident that traditional irrigation (I_1) resulted in the highest concentrations of nitrogen, phosphorus, and potassium in the wheat grains, while skipping irrigation events (I_2 and I_3) led to a significant reduction in these nutrient levels. Similarly, mycorrhizal inoculation (M_2) enhanced nutrient uptake, leading to higher N, P, and K levels than the control (M_1). The foliar application of fulvic acid and potassium silicate, especially when combined (F_4), further improved nutrient content compared to untreated plants.

Table 5 reveals a consistent trend where carbohydrate and protein contents were highest under traditional irrigation (I_1) and decreased with increasing water stress. Mycorrhizal inoculation (M_2) significantly improved both carbohydrate and protein levels compared to the control (M_1). Among foliar treatments, the combination of fulvic acid and potassium silicate (F_4) resulted in the highest biochemical values, suggesting an additive or synergistic effect.

The reduction in N, P, and K content under water stress conditions (I_2 and I_3) can be attributed to decreased root activity and nutrient uptake due to limited water availability. Water stress often impairs soil nutrient mobility and plant absorption efficiency, leading to lower mineral accumulation in grains. Mycorrhizal fungi (M_2) enhance root growth and nutrient absorption, particularly under drought conditions, by improving soil phosphorus availability and water uptake, thus explaining the higher nutrient levels in mycorrhizal-treated plants.

Table 4. Effect of skipping irrigation events, mycorrhizal, fulvic acid and potassium silicate on grain chemical traits of wheat plants after harvest during seasons of 2022/23 and 2023/24

Parameters			N, %		P, %		K, %	
Treatments			**1st season**	**2nd season**	**1st season**	**2nd season**	**1st season**	**2nd season**
Main factor: Irrigation treatments								
I_1: Traditional irrigation (5 irrigations)			2.54a	2.64a	0.294a	0.300a	1.97a	2.05a
I_2: Skipping 2 irrigations			2.41b	2.51b	0.280b	0.286b	1.85b	1.93b
I_3: Skipping 3 irrigations			2.05c	2.13c	0.240c	0.246c	1.60c	1.66c
LSD at 5%			0.03	0.04	0.005	0.002	0.07	0.07
Sub factor: Mycorrhizal treatments								
M_1: Control (Without mycorrhizal)			2.23b	2.32b	0.258b	0.264b	1.72b	1.79b
M_2: With mycorrhizal			2.43a	2.53a	0.285a	0.291a	1.89a	1.97a
LSD at 5%			0.02	0.02	0.002	0.003	0.07	0.07
Sub-sub factor: Foliar treatments								
F_1: Control (without spraying)			2.27b	2.37b	0.265	0.271d	1.77c	1.83c
F_2: Fulvic acid (FA)			2.30b	2.40b	0.269	0.275c	1.79bc	1.86bc
F_3: Potassium silicate (K_2SiO_3)			2.36a	2.45a	0.274	0.280b	1.82ab	1.90ab
F_4: FA+ K_2SiO_3			2.38a	2.48a	0.277	0.284a	1.84a	1.92a
LSD at 5%			0.04	0.05	0.003	0.003	0.05	0.06
Interaction								
I_1	M_1	F_1	2.37	2.47	0.272	0.279	1.84	1.90
		F_2	2.37	2.51	0.274	0.279	1.86	1.94
		F_3	2.47	2.54	0.283	0.289	1.88	1.97
		F_4	2.48	2.58	0.286	0.292	1.90	1.98
	M_2	F_1	2.59	2.69	0.303	0.310	2.03	2.11
		F_2	2.60	2.70	0.309	0.315	2.07	2.15
		F_3	2.69	2.80	0.313	0.319	2.07	2.15
		F_4	2.74	2.85	0.315	0.321	2.11	2.19
I_2	M_1	F_1	2.18	2.27	0.258	0.263	1.71	1.78
		F_2	2.25	2.34	0.262	0.267	1.73	1.80
		F_3	2.33	2.43	0.263	0.268	1.78	1.85
		F_4	2.33	2.44	0.268	0.273	1.79	1.87
	M_2	F_1	2.50	2.61	0.293	0.299	1.92	1.99
		F_2	2.55	2.66	0.296	0.302	1.94	2.02
		F_3	2.56	2.66	0.298	0.304	1.97	2.05
		F_4	2.58	2.70	0.302	0.309	1.99	2.08
I_3	M_1	F_1	1.96	2.04	0.225	0.231	1.48	1.54
		F_2	1.99	2.07	0.228	0.235	1.51	1.57
		F_3	2.00	2.08	0.238	0.243	1.57	1.63
		F_4	2.03	2.11	0.240	0.247	1.59	1.65
	M_2	F_1	2.06	2.14	0.241	0.246	1.62	1.68
		F_2	2.07	2.15	0.244	0.250	1.63	1.71
		F_3	2.13	2.22	0.251	0.256	1.66	1.73
		F_4	2.15	2.24	0.255	0.263	1.69	1.76
LSD at 5%			0.11	0.12	0.008	0.007	0.13	0.13

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 5. Effect of skipping irrigation events, mycorrhizal, fulvic acid and potassium silicate on grain biochemical traits of wheat plants after harvest during seasons of 2022/23 and 2023/24

Parameters			Carbohydrates, %		Protein, %	
Treatments			**1st season**	**2nd season**	**1st season**	**2nd season**
Main factor: Irrigation treatments						
I_1: Traditional irrigation (5 irrigations)			67.19a	68.51a	14.59a	15.19a
I_2: Skipping 2 irrigations			65.83b	67.21b	13.85b	14.44b
I_3: Skipping 3 irrigations			61.98c	63.25c	11.77c	12.25c
LSD at 5%			0.23	0.33	0.20	0.23
Sub factor: Mycorrhizal treatments						
M_1: Control (Without mycorrhizal)			63.64b	64.88b	12.82b	13.35b
M_2: With mycorrhizal			66.35a	67.76a	14.00a	14.56a
LSD at 5%			0.46	0.21	0.11	0.11
Sub-sub factor: Foliar treatments						
F_1: Control (without spraying)			64.43c	65.73c	13.08b	13.62b
F_2: Fulvic acid (FA)			64.77bc	66.12bc	13.25b	13.82b
F_3: Potassium silicate (K_2SiO_3)			65.03b	66.37b	13.59a	14.11a
F_4: FA+ K_2SiO_3			65.76a	67.06a	13.71a	14.29a
LSD at 5%			0.54	0.59	0.26	0.29
Interaction						
I_1	M_1	F_1	65.33	66.40	13.63	14.18
		F_2	65.32	66.65	13.61	14.41
		F_3	65.38	66.81	14.20	14.62
		F_4	66.53	67.82	14.24	14.82
	M_2	F_1	68.14	69.30	14.87	15.47
		F_2	68.45	69.84	14.95	15.51
		F_3	68.69	69.97	15.49	16.10
		F_4	69.64	71.25	15.74	16.37
I_2	M_1	F_1	63.64	65.09	12.52	13.03
		F_2	64.31	65.59	12.92	13.46
		F_3	64.63	65.92	13.40	13.95
		F_4	64.83	65.85	13.42	14.03
	M_2	F_1	66.56	68.28	14.38	14.99
		F_2	67.08	68.43	14.64	15.30
		F_3	67.71	69.21	14.72	15.28
		F_4	67.88	69.28	14.84	15.51
I_3	M_1	F_1	60.36	61.58	11.25	11.71
		F_2	60.56	61.79	11.44	11.90
		F_3	60.58	61.65	11.48	11.96
		F_4	62.25	63.43	11.67	12.13
	M_2	F_1	62.51	63.70	11.83	12.31
		F_2	62.88	64.42	11.90	12.34
		F_3	63.21	64.67	12.23	12.75
		F_4	63.45	64.75	12.36	12.86
LSD at 5%			1.31	1.44	0.63	0.70

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

The beneficial effects of fulvic acid and potassium silicate on nutrient uptake and biochemical traits can be linked to their physiological roles. Fulvic acid enhances nutrient chelation and transport within plants, improving nutrient efficiency. Potassium silicate contributes to osmotic regulation and stress tolerance by enhancing cell wall strength and reducing transpiration losses. Their combined application (F_4) showed the highest improvement, likely due to their complementary roles in enhancing nutrient uptake and stress mitigation.

The decline in carbohydrate and protein content under water stress (I_2 and I_3) is expected due to reduced photosynthetic activity and protein synthesis under drought conditions. Mycorrhizal improved these traits by enhancing root-water relations and nutrient assimilation. The increase in protein content with fulvic acid and potassium silicate treatments (especially F_4) suggests that these compounds play a role in nitrogen metabolism and stress resilience, leading to improved grain quality even under limited irrigation.

Overall, it can be said that traditional irrigation, mycorrhizal inoculation, and foliar applications, particularly the combination of fulvic acid and potassium silicate, significantly enhanced wheat grain nutritional quality under normal and drought-stressed conditions. These findings are in accordance with those of Hamed *et al.* (2021); Rafie *et al.* (2021); Salem *et al.* (2022); Saudy *et al.* (2023); Abdelaal *et al.* (2024).

CONCLUSION

Water deficit significantly reduced wheat performance in terms of activity of enzymatic antioxidants and nutritional status, with traditional irrigation (I1) providing the best results. Mycorrhizal inoculation (M2) and foliar application of fulvic acid and potassium silicate (F4) effectively mitigated drought stress by enhancing water and nutrient uptake, reducing oxidative stress and improving yield. For sustainable wheat production under water scarcity, integrating mycorrhizal inoculation with foliar application of fulvic acid and potassium silicate is recommended. Future research should optimize irrigation strategies, explore additional bio stimulants, and utilize precision agriculture to enhance drought resilience and water use efficiency.

Abbreviations: POD: Peroxidase, CAT: Catalase, SOD: Superoxide dismutase, MDA; Malondialdehyde, as a lipid peroxidation marker

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التأثير المحتمل للتلقيح بالمايكورايزا، وحمض الفولفيك، وسليكات البوتاسيوم على نشاط مضادات الأكسدة الإنزيمية والحالة الغذائية للقمح النامي تحت ظروف تخطي بعض مواعيد الري

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الملخص

نظرًا لأهمية القمح كمحصول استراتيجي والتحديات المتزايدة التي يفرضها نقص المياه، فان هذه الدراسة تهدف الى تقييم التأثير التكاملي لتلقيح الميكروهايزا، وحمض الفولفيك، وسيليكات البوتاسيوم على نشاط مضادات الأكسدة الإنزيمية في أوراق القمح والحالة الغذائية للحبوب تحت ظروف تخطي بعض مواعيد الري. تم تنفيذ التجربة باستخدام تصميم القطاعات المنشقة مرتين، حيث مثّلت معاملات الري العامل الرئيسي (I_1: ٥ ريات تم تنفيذهم،I_2: ٣ ريات تم تنفيذهم،I_3: ريتان تم تنفيذهم).العامل المنشق الأول كان الميكروهايزا (M_1: بدون تلقيح،M_2: بالتلقيح).العامل المنشق الثاني كان الرش الورقي (F_1: بدون رش،F_2: حمض الفولفيك ،F_3: سيليكات البوتاسيوم ،F_4: مزيج من حمض الفولفيك وسيليكات البوتاسيوم).سُجلت أعلى مستويات من إنزيمات البيروكسيديز(POD) ، والكاتالاز(CAT) ، والسوبر أوكسيد ديسميوتاز(SOD) ، ومادة المالونداياللديهايد (MDA) تحت الإجهاد المائي الشديد(I_3) ، بينما لوحظت أدنى القيم تحت الري التقليدي(I_1) . أدى التلقيح بالمايكورايزا (M_2) إلى تقليل الإجهاد التأكسدي بشكل ملحوظ مقارنةً بالمعاملة غير الملقحة (M_1) .كما أدى الجمع بين حمض الفولفيك وسليكات البوتاسيوم (F_4) إلى أدنى مستويات لنشاط مضادات الأكسدة الإنزيمية ومركب المالونداياللديهايد. حقق الري التقليدي (I_1) أعلى القيم للنيتروجين والفوسفور والبوتاسيوم، والكربوهيدرات، والبروتين في الحبوب، في حين أدى تخطي الري (I_2) و (I_3) إلى انخفاض معنوي في هذه الصفات. كذلك، أدت المعاملة بـ M_2 إلى تحسين محتوى النيتروجين والفوسفور والبوتاسيوم والكربوهيدرات والبروتين مقارنةً بالمعاملة M_1. وساهم الرش الورقي بحمض الفولفيك وسليكات البوتاسيوم، خاصةً عند استخدامهما معًا(F_4) ، في تحسين المحتوى الغذائي وصفات الجودة بشكل أكبر مقارنةً بالنباتات غير المعاملة.