RESPONSE OF BREAD WHEAT YIELD AND COMPONENTS TO FOLIAR SILICON UNDER MOISTURE DEPLETION CONDITIONS

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ABSTRACT

Thi study aimed to assess the physiological effect of foliar silicon on the yield and its components of Bohouth 22cultivar bread wheat under conditions of moisture depletion. A field experiment was conducted at the Research Station E, College of Agricultural Engineering Sciences, University of Baghdad (Al-Jadriyah), during the 2022-2023 and 2023-2024 winter seasons. The nested design with three replicates was used to study three levels of moisture depletion (40%, 60%, and 80%) and four silicon concentrations (0, 150, 200, and 250 mg L^{-1}).The results showed significant effects of depletion levels and silicon concentrations, with 40% and 60% depletion achieving the highest values for the yield and its components. mean yields for the two seasons reached 5.627 and 4.792 t ha^{-1}, and the highest water use efficiency for grain yield for the 60% depletion level compared to the 40% depletion factor reached 2.49 kg m^3 of water in grains, and their water consumption reached 350.35 mm $Season^{-1}$, which made 12.18% of water availability for the two seasons. The lowest values were recorded at the depletion level of 80%.The silicon concentration of 200 mg L^{-1} also improved the yield and its components, as a mean for the two seasons. The grain yield reached 5.338 t h^{-1}, and the water use efficiency of the grain yield amounted to 2.64 kg grains m^{-3} water compared to the control treatment sequentially. The interaction of the two study factors also had a significant effect on Most of the attributes.

Keywords: physiological effect, plant cell potential, relative water, climate change, environmental stress

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مجلة العلوم الزراعية العراقية- 2025: 56: (4):1492-1503 دلي وعلك

استجابة حاصل حنطة الخبز ومكوناته لرش السيليكون الورقي تحت ظروف الاستنزاف الرطوبي

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المستخلص

هدفت الدراسة إلى تقييم الأثر الفسيولوجي للرش الورقي بالسيليكون على الحاصل ومكوناته لصنف حنطة الخبز بحوث 22 تحت ظروف الاستنزاف الرطوبي. نُفذت تجربة حقلية في محطة أبحاث E، كلية علوم الهندسة الزراعية، جامعة بغداد (الجادرية)، خلال الموسمين الشتويين 2022–2023 و2023–2024. استعمل التصميم المعشش بثلاث مكررات لدراسة ثلاثة مستويات من الاستنزاف الرطوبي (40% و 60% و80%) وأربعة تراكيز من السيليكون (0، 150، 200، و250 ملغم لتر$^{-1}$). أظهرت النتائج تأثيرات معنوية لمستويات الاستنزاف وتراكيز السيليكون، حيث حقق الاستنزاف 40% و60% أعلى القيم للحاصل ومكوناته بلغ الحاصل كمتوسط للموسمين 5.627 و4.792 ط هـ$^{-1}$ واعلى كفاءة لاستعمال الماء لحاصل الحبوب لمستوى الاستنزاف 60% قياسا بمعاملة الاستنزاف 40% بلغ 2.49 كغم حبوب م^3 ماء واستهلاكها المائي بلغ 350.35 مم موسم$^{-1}$، مما توافر 12.18% من المياه للموسمين, واقل القيم سجلها مستوى الاستنزاف 80%,كما حسّن تركيز السيليكون 200 ملغم لتر$^{-1}$ الحاصل ومكوناته كمتوسط للموسمين بلغ حاصل الحبوب بلغ 5.338 ط هـ$^{-1}$ وكفاءة استعمال الماء لحاصل الحبوب بلغت 2.64 كغم حبوب م$^{-3}$ماء قياساً مع معاملة المقارنة بالتتابع ، كما أثر تداخل عاملي الدراسة معنوياً في اغلب الصفات.

كلمات مفتاحية: الاثر الفسيولوجي, جهد الخلية النباتية, الماء النسبي, التغير المناخي, الاجهاد البيئي

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INTRODUCTION

Bread Wheat (*Triticum aestivum* L.) important crop in Iraq and World. The world, including Iraq, faces significant challenges due to drought, which stands as the most critical threat to agricultural production (2, 3, 16). Drought, driven by climate change phenomena such as global warming, reduced rainfall, and desertification, exerts a profound impact on plant growth (1, 18). Iraq, classified as part of the arid and semi-arid regions, faces substantial challenges regarding water scarcity. This is particularly critical because the primary sources of water for the Tigris and Euphrates rivers, which sustain the country's agricultural lands, originate from neighboring countries, making water a vital limiting factor for agricultural production. This reality has drawn the attention of researchers to the importance of optimizing water usage through modern strategies that minimize wastage and ensure sustainable practices. Foliar fertilization, with its high content of readily available nutrients and rapid absorption and distribution in plants, is an effective measure aimed at enhancing and increasing crop yields. Moreover, modern agriculture increasingly relies on foliar fertilization, particularly for cereal crops (30). Among these is foliar silicon fertilization, which is recognized as a beneficial nutrient with a critical role in agriculture. Its importance lies in alleviating the effects of water stress by regulating cellular osmotic pressure, improving plant water status through the regulation of transpiration, maintaining carbon assimilation rates, and enhancing nutrient uptake and soluble sugar content in flag leaf (29). This is achieved by preserving tissue water status and preventing cellular damage caused by drought, thereby supporting cell turgor. Silicon facilitates the accumulation of various organic and inorganic solutes, such as sugars, in the cell sap (14, 19, 27). Additionally, It performs a protective role by forming a physical barrier that strengthens cell walls, reducing the harmful effects of water stress. This is achieved by increasing the thickness of the epidermis and the silica-deposited epidermal layer (6 , 25), thereby enhancing water use efficiency through reduced stomatal transpiration (32). Silicon foliar application increased spike weight due to silica deposition and cell division and elongation (13). Silicon spraying increased wheat spike length (8).Silicon spraying promotes the initiation and development of bud primordia, leading to an increase in the number of spikes (15). and contributes to an increase in 1000-grain weight (22 , 30). silicon application enhanced wheat grain yield (9 , 10).

MATERIALS AND METHODS

Two field experiments were conducted during the 2022-2023 and 2023-2024 winter seasons in the research station E, College of Agricultural Engineering Sciences, University of Baghdad (Jadiriyah). The soil characteristics are presented in Table (1). The study aimed to investigate the effect of foliar silicon application on grain yield, its components, water use efficiency, and water consumption of bread wheat grown under water stress conditions. A nested design with three replicates was used. The main plots included three irrigation treatments based on 40%, 60%,and 80% depletion of available water for plants, denoted as I_1, I_2, and I_3, respectively. The subplots involved foliar application of silicon at concentrations of 150, 200, and 250 mg L^{-1}, labeled as Si_1, Si_2, Si_3 respectively, along with a control treatment (spraying with distilled water only), denoted as Si_0.

Table 1. Chemical and physical properties of the field soil for the two seasons (2022-2023 at the top and 2023-2024 at the bottom).

	Parameter	Value	Unit of measurement
	PH of Soil	7.24	-
		7.00	
	Ec	1.10	Ds m^{-1}
		0.80	
	CEC	21.24	Cent.mal.$Charge^{-1}$
		18.90	
Available ions	Silicon	86.00	mg kg^{-1} soil
		72.53	
	Nitrogen	16.80	
		12.00	
	Phosphor	6.14	
		5.23	
	Potassium	113.57	
		109.42	
Soil Separators	Sand	432	Kg^{-1} soil
	Silt	225	
	Clay	343	
	Soil texture	Sandy loamy	-
	Bulk density	1.64	Mica grams m^{-3}
	V.M.C(*Fc*)(33kPa)	0.300	cm^3 cm^{-3}
	V.M.C(*pwp*)(1500)kPa	0.120	
	Available Water	0.180	

The experimental field was prepared for two growing seasons by plowing it twice in perpendicular directions, followed by leveling and smoothing. The field was then divided into plots according to the aforementioned design. Each experimental unit covered an area of 4 m², consisting of 10 rows, each 2 meters long, with 20 cm spacing between rows. A buffer zone of 2 meters was maintained between the main treatments and between replicates to control horizontal water movement and prevent water seepage from irrigated to non-irrigated plots. Bread wheat seeds of the cultivar buhooth 22, supplied by the agricultural research directorate, and were sown manually on December 7, 2023, for the first season and November 28, 2024, for the second season, at a seeding rate of 120 kg ha^{-1}. The experimental fields were fertilized with urea at a rate of 180 kg ha^{-1}(46% N) (**20**), applied in two equal doses: at tillering and the booting stage, following the Zadoks growth scale. Triple superphosphate was applied at a rate of 100 kg ha^{-1} (21% P_2O_5) as a single dose during soil preparation. Potassium fertilizer was applied as potassium sulfate (K_2SO_4, 41.5% K) in two doses at a rate of 150 kg ha^{-1} : at sowing and at the beginning of stem elongation (**12**). Weeds were removed manually whenever necessary. The plants from both experiments were harvested upon reaching full maturity on May 1, 2023, for the first winter season and April 20, 2024, for the second season. The relationship between volumetric water content (θ) and matric potential (W) was determined for soil samples sieved through a 2 mm mesh. The moisture content was measured at matric potentials of 0, 3, 5, 7, and 15 bars in the Soil and Water Resources Laboratory, College of Agricultural Engineering Sciences, University of Baghdad. This analysis aimed to estimate the soil's water-holding capacity at a depth of 0–40 cm and determine the available water content by calculating the difference between the volumetric water content at field capacity and permanent wilting point, as presented (Table 1).The volumetric method was used to measure the soil moisture content by collecting soil samples using an auger at depths of 30 and 40 cm one day before irrigation. The samples were placed in aluminum containers and weighed while wet. They were then dried in a microwave oven for 12 minutes after calibrating the drying duration using samples dried in an electric oven at 105°C for 24 hours, according to the method proposed by Mohamad *et al.*, (**26**). The moisture content was then determined using the following equation (**17**):

$$\mathrm{Pw} = \frac{\mathrm{Msw-Ms}}{\mathrm{Ms}} \times 100 \quad \text{…….. (1)}$$

Where:

Pw = Percentage of moisture by weight

Msw = Wet soil mass (g)

Ms = Dry soil mass (g).

The volumetric moisture content was calculated based on the soil bulk density using the following equation:

$Q = Pw \times Pb$ **……………(2)**

Where:

Q = Volumetric moisture content.

Pw = Moisture content by weight

Pb = Soil bulk density (Mg m^{-3}).

Irrigation was carried out using flexible plastic pipes connected to a gasoline-powered pump with a constant discharge rate, equipped with a meter to measure the amount of water added (in liters) to each experimental unit. The water quantities were calculated based on the depletion of soil moisture during the two winter seasons. Equal amounts of water were initially added to all experimental units to ensure uniform field emergence. Water stress treatments (40%, 60%, and 80% of available water) were applied once the plants reached the tillering stage. The irrigation volumes for a 30 cm depth per application were 86.4, 129.6, and 172.8 liters per experimental unit, respectively. For a 40 cm depth, the volumes were 115.2, 172.8, and 230.4 liters per experimental unit, respectively, and continued until the final irrigation at physiological maturity during both seasons. The depth of water added to compensate for depleted moisture .

Preparation of Silicon (Si) Foliar Spray

Raw silicon (Si) with a purity of 0.99 was obtained from Thomas Baker Company, India. A stock concentration of 1000 mg L^{-1} was prepared as a suspension by adding a few drops of hydrochloric acid to dissolve 1g of raw silicon powder (Si) as an auxiliary agent. The silicon was dissolved in one liter of distilled water with continuous stirring at room temperature until a homogenous solution was obtained. This resulted in a standard solution (original) with a concentration of 1000 mg L^{-1} (**5**). For the other required concentrations, the same preparation steps were followed, without adding an auxiliary agent, using the following dilution equation: $N_1 \times V_1 = N_2 \times V_2$ **…..(3)**

Where: N_1= Concentration of the stock solution (mg L^{-1}).

V_1= Volume of the stock solution (L).

N_2 = Desired concentration (mg L^{-1}).=

V_2= Desired volume (L).

The plants were sprayed with the silicon solution on the vegetative parts during both seasons, with three applications at specific growth stages according to the Zadoks scale.

First spray: At the early tillering stage ZGs_{22} (main stem + one tiller).

Second spray: During the stem elongation stage ZGs_{33} (three nodes on the main stem).

Third spray: At the flowering stage ZGs_{61}

The spraying was conducted early in the morning to avoid high temperatures, using a 16-liter backpack sprayer. Spraying continued until complete wetting of the plants was achieved, with the first droplet falling off the leaves. A small amount of a surfactant (detergent) was added to the solution to reduce water surface tension and ensure uniform wetting of the leaves. These procedures were carried out consistently for all spraying times during both seasons.

Measured Traits: A 1-meter length of the central rows from each experimental unit was sampled to measure yield and its components, including number of spikes, number of spikelets per spike, number of grains per spike, 1000-grain weight, and grain yield at full maturity. Water use efficiency (WUE) for grain yield was calculated using the following equation (**24**):

WUE = GY / W.A

Where:

WUE = Water use efficiency (kg grains m^{-3} water).

GY = Grain yield (kg ha^{-1}).

W.A = Applied irrigation water (m^3 ha^{-1}).

Water Consumption: Water consumption was determined based on soil moisture content measured after irrigation and before the next irrigation at depths of 30 and 40 cm.

Statistical Analysis: The experimental data were analyzed statistically using the Genstat software analyses of variance according to the design employed. Treatment means were compared using the least significant difference (LSD) at the 5% level of significance (31).

RESULTS AND DISCUSSION

Number of Spikes (spikes m^{-2}): The results in Table (2) show that the I_1 and I_2 treatments achieved the highest mean number of spikes per unit area, with 359.75 and 345.00 spikes m^{-2}, respectively, with no significant difference between them in the first season. In the second season, these treatments recorded 354.50 and 338.25 spikes m^{-2}, respectively, with a significant difference between them. In contrast, the I_3 treatment recorded the lowest mean, with 340.75 and 327.25 spikes m^{-2} for the two seasons, respectively. The decrease in the mean number of Spikes in the depletion treatment I_3 may be attributed to a decrease in the accumulation and transfer of materials resulting from the carbon metabolism process in the Tillering stage to other parts of the plant as a result of the lack of moisture content in the soil. This hindered further growth and spike formation under water stress conditions. These findings align with those of Al-Desuquy *et al.* (4) and Ati *et al.* (7), who reported that reduced light interception due to decreased leaf growth and expansion in wheat plants resulted in the death of young tillers under water stress conditions. The Si_3 treatment recorded the highest mean number of 359.66 spikes m^{-2} in the first season, with no significant difference from the Si_2 treatment. In the second season, the Si_2 treatment was superior, recording the highest mean number of 353.33 spikes m^{-2}, compared to the control Si_0, which had the lowest mean number of 332.33 and 311.00 spikes m^{-2} for the first and second seasons, respectively. The reason for the increase may be attributed to Silicon contribution to regulating the action of hormones responsible for bud emergence, as well as activating the action of enzymatic antioxidants to reduce ROS damage. Silicon-treated plants exhibited enhanced photosynthetic activity, hormonal balance, and enzymatic activity, which promoted the development of a larger vegetative canopy and increased the number of flowering tillers. This positively impacted the number of spikes. These findings are consistent with Haijun *et al.* (15), who reported that silicon application in wheat plants increases the number of spikes per square meter. The combinations I_1Si_2, I_1Si_3, and I_2Si_1 achieved the highest mean for the number of spikes, recording 377.00, 377.00, and 375.00 spikes m^{-2},for season1 respectively, with no significant differences among them. These were significantly superior to the control combination I_3Si_0, which recorded the lowest mean number of 331.00 spikes m^{-2}, with no significant difference from I_1Si_0 and I_2Si_0 for the first season. In the second season, the combination I_2Si_2 recorded the highest mean number of 374.00 spikes m^{-2}, significantly outperforming the control combination I_2Si_0, which recorded the lowest mean of 310.00 spikes m^{-2}, with no significant difference from I_1Si_0 and I_3Si_0. These interaction results highlight the positive role of silicon in enhancing the number of spikes under all moisture depletion conditions. Increasing silicon spray concentrations consistently improved spike numbers across all moisture depletion treatments. Silicon's role in regulating plant growth and enhancing its ability to tolerate water stress conditions was evident. These findings align with those of Aurangzaib *et al.* (8), who reported that silicon spraying increased the number of spikes per unit area under water stress conditions.

Table 2. Response of number of spikes (spikes m^{-2}) to moisture depletion, foliar silicon and their interaction for the two winter seasons (2022-2023 at the top and 2023-2024 at the bottom).

Available Water Depletion Level (%)	Silicon Spray Concentrations (mg L^{-1})				Mean for two season
	Si_0	Si_1	Si_2	Si_3	
	0	150	200	250	
%40 I_1	333.00	352.00	377.00	377.00	357.37
	313.00	356.00	356.00	355.00	
%60 I_2	333.00	375.00	358.00	352.00	346.38
	310.00	333.00	374.00	336.00	
%80 I_3	331.00	340.00	342.00	350.00	334.00
	310.00	338.00	330.00	331.00	
Mean	332.33	355.66	359.00	359.66	
	311.00	342.33	353.33	340.66	
$LSD_{0.05}$	I	Si	Int		
	9.90	4.40	8.80		
	5.10	8.50	13.30		

Number of spikelets per spike (spikelets spike^{-1}): The results in Table (3) show that the I_1 treatment recorded the highest mean number of spikelets per spike, with 20.08 and 18.95 spikelets spike^{-1} for the first and second seasons, respectively. This did not differ significantly from the I_2 treatment, which recorded mean of 19.57 spikelets spike^{-1} in the first season and 18.00 spikelets spike^{-1} in the second season. Conversely, the I_3 treatment recorded the lowest mean of 18.86 and 17.65 spikelets spike^{-1} for the two seasons, respectively. The reduction in the number of spikelets per spike under the I_3 treatment may be attributed to the high water stress, which reduced flag leaf area, light interception, and the number of spikes (Table2), leading to the death of some tillers, decreased the photosynthetic activity of the leaves. Together, these factors contributed to a lower number of spikelets per spike under water stress conditions. This result aligns with the findings of Al-Desuquy *et al*. (**4**). The Si_2 treatment significantly outperformed other treatments, recording the highest mean number of 20.38 and 18.66 spikelets spike^{-1} for the first and second seasons, respectively. However, it did not differ significantly from other silicon spray concentrations. In contrast, the control treatment Si_0, recorded the lowest mean number of 18.27 and 17.46 spikelets spike^{-1} for the two seasons, respectively. This increase may be attributed to the role of silicon in stabilizing and accumulating assimilates from photosynthesis in developing plant tissues. Silicon deposition in the cell walls induces anatomical changes, such as cell wall thickening, cell division, elongation, and membrane stability. These changes likely improve water relations, enhancing plant growth. This finding is consistent with Faraz *et al*., (**13**), who reported similar improvements in spikelet formation due to silicon application.

Table 3. Response number of spikelets per spike (spikelets spike^{-1}) to moisture depletion, foliar silicon and their interaction for the two winter seasons (2022-2023 at the top and 2023-2024 at the bottom).

Available Water Depletion Level (%)	Silicon Spray Concentrations (mg L^{-1})				Mean for two season
	Si_0	Si_1	Si_2	Si_3	
	0	150	200	250	
%40 I_1	18.51	20.45	20.98	20.39	19.52
	18.30	19.20	19.70	18.60	
%60 I_2	18.41	19.61	20.57	19.70	18.78
	17.30	18.10	18.40	18.20	
%80 I_3	17.90	18.90	19.60	19.07	18.25
	16.80	17.80	17.90	18.10	
Mean	18.27	19.65	20.38	19.72	
	17.46	18.36	18.66	18.30	
LSD $_{0.05}$	I	Si	Int		
	0.56	0.55	N.S		
	0.35	0.32	N.S		

Number of grains per spike (grains spike^{-1})
The results in Table (4) show that the I_1 treatment recorded the highest average number of grains per spike, with 51.25 and 46.75 grains spike^{-1} for the first and second seasons, respectively. These values were significantly higher than those recorded by I_2 and I_3 , which mean number 47.00 and 45.25 grains spike^{-1}, and 45.00 and 42.25 grains spike^{-1} for the two seasons, respectively. The reduction in the number of grains per spike in the I_3 treatment can be attributed to the adverse effects of reduced soil moisture availability on pollen viability and activity, resulting in weaker fertilization of ovules in the spikelets. This ultimately led to fewer grains per spike. These findings align with those reported by Poudel *et al*.,(**28**), who confirmed that the number of grains per spike decreases with varying moisture depletion levels, with an mean reduction of 15.32% under water stress conditions. The results indicated that silicon spraying at different concentrations led to an increase in the mean number of grains per spike. The Si_1 and Si_2 treatments significantly recorded the highest mean, with 49.00 and 50.33 grains spike^{-1}, respectively, with no significant difference between them for the

first season. In the second season, Si_2 and Si_3 treatments recorded the same average of 45.66 grains spike^{-1}, with no significant difference from the Si_1 treatment In contrast, the control treatment Si_0 recorded the lowest mean of 44.33 and 42.66 grains spike^{-1} for the two seasons, respectively. The increase may be in the mean number of grains per spike can be attributed to the plant's response to silicon in enhancing the plant's water status by increasing the relative water content, which resulted in an increase in the mean number of spikelets per spike, which was reflected in the number of grains per spike (Table 3). This improved the efficiency of carbon assimilation, resulting in greater dry matter accumulation and its translocation to sink tissues, including the spike (Table 2). These effects positively influenced the number of grains per spike. These findings are consistent with those of Stankowski *et al.* (**30**), who highlighted silicon's role in increasing the number of grains per spike. The combination I_1Si_2 recorded the highest average number of grains per spike , reaching 49.00 grains spike^{-1} significantly outperforming all other combinations. Conversely, the combinations I_2Si_0 , I_3Si_1, I_3Si_2, I_3Si_3 shared the lowest mean of 42.00 grains spike^{-1}, with no significant difference from the control combination I_3S_0 for the second season only. These findings suggest that silicon plays a crucial role in regulating plant growth and enhancing its ability to withstand water stress. Water deficiency reduces pollen grain fertility, increases the number of unfertilized spikelets, and ultimately decreases the number of grains per spike. This conclusion aligns with the results of Aurangzaib *et al.* (**8**), who noted that foliar application of silicon enhances wheat's ability to tolerate water stress, positively impacting the number of grains per spike.

Table 4. Response of number of grains per spike (grains spike^{-1}) to moisture depletion, foliar silicon and their interaction for the two winter seasons (2022-2023 at the top and 2023-2024 at the bottom)

Available Water Depletion Level (%)	Silicon Spray Concentrations (mg L^{-1}) Si_0 0	Si_1 150	Si_2 200	Si_3 250	Mean for two season
%40 I_1	46.00	53.00	55.00	51.00	49.00
	43.00	47.00	49.00	48.00	
%60 I_2	44.00	47.00	50.00	47.00	46.00
	42.00	45.00	46.00	47.00	
%80 I_3	43.00	47.00	46.00	45.00	43.75
	43.00	42.00	42.00	42.00	
Mean	44.33	49.00	50.33	47.66	
	42.66	44.66	45.66	45.66	
LSD $_{0.05}$	I	Si	Int		
	1.90	2.20	N.S		
	0.40	1.40	2.10		

1000-grains weight (g)

Data in Table (5) show that increased water depletion consistently reduced the weight of 1000 grains, with the lowest weight recorded under the I_3 treatment mean number 28.35 g and 27.35 g for the first and second seasons, respectively . The reduction in the 1000-grain weight under the I_3 treatment may be attributed to the adverse effects of water stress, which decreased the accumulation of assimilates from source tissues to sink tissues. This was most likely due to the decrease in respiration and carbon fixation processes that contribute to the process of accumulation and transfer of the products of the carbon assimilation process to their places of accumulation in the grains, the decrease in relative water content, and the shortening of the grain filling period under conditions of moisture depletion, which ultimately led to a decrease in grain weight. The results revealed that the Si_1 and Si_2 treatments significantly outperformed others in achieving the highest average 1000-grain weights of 31.60 g in the first season and 31.10 g in the second season. In contrast, the control treatment Si_0 recorded the lowest mean number of 27.33 g and 26.74 g for the two seasons, respectively. The increase in weight of 1000 with silicone spraying can be attributed to its role in maintaining the cell membrane to relieve the pressure of water depletion on it, which led to a longer period of accumulation and filling of the grains with materials resulting from the carbon metabolism process. These factors allowed for better utilization of carbon assimilates as reserves, contributing to the increased grain weight. These results are consistent with those of Kobra *et al*.,(**22**), who found that silicon application during wheat growth stages positively affects biomass accumulation and increases 1000-grain weight.

Table 5. Response of 1000-Grain weight (g) to moisture depletion, foliar silicon and their interaction for the two winter seasons (2022-2023 at the top and 2023-2024 at the bottom).

Available Water Depletion Level (%)	Silicon Spray Concentrations (mg L^{-1}) Si_0 0	Si_1 150	Si_2 200	Si_3 250	Mean for two season
%40 I_1	28.60	34.00	32.20	33.40	32.31
	28.57	33.37	33.63	34.67	
%60 I_2	27.20	31.40	30.20	31.50	29.85
	26.20	30.73	31.47	30.13	
%80 I_3	26.20	29.40	30.50	27.30	27.85
	25.47	27.63	28.20	28.10	
Mean	27.33	31.60	30.96	30.73	
	26.74	30.57	31.10	30.96	
$LSD_{0.05}$	I	Si	Int		
	1.07	1.23	N.S		
	1.16	1.21	N.S		

Grain yield (t ha^{-1})

The results in Table (6) reveal A treatments I_1 and I_2 showed similar effects, both achieving the highest grain yields. I_1 recorded mean number of 5.955 and 5.300 t ha^{-1} for the first and second seasons, respectively, while I_2 recorded mean number of 5.020 and 4.565 t ha^{-1} for the two seasons, respectively. In contrast, the I_3 treatment resulted in the lowest grain yield, with mean number of 4.372 and 3.778 t ha^{-1} for the first and second seasons, respectively. The reduction in grain yield under I_3 may be attributed to the negative impact of water stress, which led to a decrease in one or more yield components, such as the number of spikes, number of spikelets per spike, number of grains per spike, and 1000-grain weight (Tables 2, 3, 4, and 5, respectively). These reductions collectively affected the final grain yield. The results indicate that silicon spray treatments provided some protection to plants against water stress. This was evident in the significant superiority of the Si_2 treatment over the control, achieving the highest mean number grain yields of 5.623 and 5.054 t ha^{-1} for the first and second seasons, respectively. In contrast, the control treatment Si_0 recorded lower grain yields of 4.030 and 3.550 t ha^{-1} for the two seasons, respectively. The increase in grain yield with silicon spraying can be attributed to an improvement in key yield components such as the number of spikes (Table 2), number of grains per spike (Table 4), and 1000-grain weight (Table 5). Additionally, silicon's role in regulating the plant's water status supported enzymatic activity and enhanced carbon assimilation efficiency, leading to the accumulation of proteins and carbohydrates in the grains. These findings align with those of Bendidi *et al.* (**9**) and Bukhari *et al.* (**10**), who reported that silicon application increased grain yield. The results demonstrated a significant interaction between available water depletion treatments and silicon spray concentrations. The I_1Si_2 combination recorded the highest mean number grain yield of 6.670 t ha^{-1}, with no significant difference from the I_1Si_1 and I_1Si_3 combinations for the first season. In the second season, the I_1Si_3 combination achieved the highest mean grain yield of 5.907 t ha^{-1}, with no significant difference from I_1Si_2 Conversely, the control combination I_3Si_0 recorded the lowest mean of 3.720 and 3.376 t ha^{-1} for the two seasons, respectively. The two study factors interacted in different directions, with grain yield initially increasing at higher treatment levels before declining under the influence of the other factor. The yield increase in these combinations can be attributed to their superior performance in key yield components (number of spikes, number of grains per spike, and 1000-grain weight). This underscores the effectiveness of silicon spraying in mitigating the damage caused by water stress, thereby improving grain yield. These findings are consistent with the results of Karmollachaab *et al.* (**21**), who reported a positive effect of silicon on grain production in wheat under water stress conditions.

Table 6. Response of Grain yield (t ha^{-1}) to moisture depletion, foliar silicon and their interaction for the two winter seasons (2022-2023 at the top and 2023-2024 at the bottom).

Available Water Depletion Level (%)	Silicon Spray Concentrations (mg L^{-1})				Mean for two season
	Si_0	Si_1	Si_2	Si_3	
	0	150	200	250	
%40 I_1	4.380	6.350	6.670	6.420	5.627
	3.842	5.583	5.868	5.907	
%60 I_2	3.990	5.520	5.400	5.170	4.792
	3.434	4.639	5.419	4.768	
%80 I_3	3.720	4.700	4.800	4.270	4.075
	3.376	3.958	3.877	3.903	
Mean	4.030	5.523	5.623	5.286	
	3.550	4.726	5.054	4.859	
LSD $_{0.05}$	I	Si	Int		
	0.31	0.32	0.54		
	0.13	0.27	0.42		

Water use efficiency (kg grain m^{-3} water)

The results in Table (7) show that the I_2 treatment significantly outperformed others, achieving the highest mean water use efficiency of 3.31 and 1.68 kg grain m^{-3} water for the first and second seasons, respectively. There was no significant difference between I_2 and I_3 for the second season. Conversely, the I_1 treatment recorded the lowest mean number of 3.00 and 1.56 kg grain m^{-3} water for the two seasons, respectively. The increased water use efficiency in the I_2 treatment indicates that the water applied was lower than that in I_1 (Table 8), leading to maximum utilization of the available water to produce a grain yield comparable to that of I_1.This may also be attributed to reduced evaporation due to greater soil shading by the crop canopy, which subsequently lowered water consumption (Table 8). The results in the same table (7) show that silicon spray treatments significantly outperformed the control Si_0. The Si_1 and Si_2 treatments achieved the highest consumption of water use efficiency, recording 3.39 and 3.44 kg grain m^{-3} water for the first season, respectively, with no significant difference between them. For the second season, Si_2 and Si_3 treatments recorded averages of 1.84 and 1.70 kg grain m^{-3} water, respectively, significantly outperforming the control Si_0, which recorded the lowest mean number of 2.49 and 1.31 kg grain m^{-3} water for the two seasons, respectively. This improvement in water use efficiency with higher silicon concentrations may be attributed to the crucial role of silicon in enhancing the plant's water status. Silicon regulates the opening and closing of stomata, as well as the length and width of the stomata, and contributes to the formation of a layer under the epidermis, which reduces water loss through transpiration, which enhances vegetative growth and improves plant productivity. This helps maintain relative water content within plant tissues, positively affecting water use efficiency. Additionally, silicon spraying may indicate its ability to mitigate the adverse effects of water stress on grain yield (Table 6), further enhancing water use efficiency. These findings align with those of Cooke and Leishman.,(**11**) and Liang *et al.* (**23**) who confirmed that silicon reduces the damage caused by water stress, improves water use efficiency, and minimizes water loss from the leaf surface by reducing transpiration.

Table 7. Response of water use efficiency (kg grain m^{-3} water) to moisturel depletion, foliar silicon and their interaction for the two winter seasons (2022-2023 at the top and 2023- 2024 at the bottom).

Available Water Depletion Level (%)	Silicon Spray Concentrations (mg L^{-1})				Mean for two season
	Si_0	Si_1	Si_2	Si_3	
	0	150	200	250	

%40	I_1	2.21	3.20	3.36	3.23	2.28
		1.19	1.63	1.82	1.63	
%60	I_2	2.64	3.64	3.56	3.41	2.49
		1.26	1.71	2.00	1.76	
%80	I_3	2.64	3.33	3.41	3.03	2.38
		1.48	1.74	1.71	1.72	
Mean		2.49	3.39	3.44	3.22	
		1.31	1.69	1.84	1.70	
$LSD_{0.05}$		I	Si	Int		
		0.16	0.19	N.S		
		0.09	0.13	N.S		

Actual water consumption (ETa) (mm season^{-1}): The results in Table (8) show the mean actual water consumption (ETa) for bread wheat during the two winter seasons. Differences in ETa values were observed across the available water depletion levels, attributed to variations in irrigation levels applied at different depletion thresholds, the number of irrigations, and rainfall during the growing season. The I_1 treatment recorded the highest mean ETa, with 401.70 mm season^{-1} and 396.20 mm season^{-1} for the first and second seasons, respectively, with a two-season mean number of 398.95 mm season^{-1}. This was followed by the I_2 treatment, which recorded ETa values of 354.90 mm season^{-1} and 345.80 mm season^{-1} for the first and second seasons, respectively, with a two-season mean number of 350.35 mm season^{-1}. The I_3 treatment recorded the lowest ETa, with 344.10 m season^{-1} and 317.00 mm season^{-1} for the two seasons, respectively, and a two-season mean of 330.55 mm season^{-1}. The percentage reduction in water consumption for the I_2 and I_3 treatments compared to I_1 mean number 12.18% and 17.14%, respectively, over the two seasons. These reductions could be utilized to expand the cultivated area for this crop and other crops. Additionally, the results indicates that the water consumption for the I_1 treatment was the highest, which is expected since the soil moisture in this treatment was maintained close to field capacity. Perhaps the decrease in the relative availability of water in the tissues and cells of the wheat plant as a result of moisture depletion from the soil over the long period of growth contributed to the total grain production of the wheat crop (Table 6), which led to an increase in the amount of water lost through the evaporation process.

Table 8. mean actual water consumption (ETa) for bread wheat for the two seasons (2022-2023 at the top and 2023-2024 at the bottom).

Depletion Levels	No. of Irrigations	Water Used (m³ ha^{-1})	Depth Water Added (mm season^{-1})	Rainfall Depth (mm)	Contribution Soil Water (mm)	Moisture Storage Depth (mm)	Actual Water Consumption (mm season^{-1})	mean ET_a(mm for two seasons^{-1})
I_1 (%40)	8	1980.00	198.00	203.7	0	0	401.70	398.95
	12	3204.00	320.40	75.8	0	0	396.20	
I_2 (%60)	5	1512.00	151.20	203.7	0	0	354.90	350.35
	8	2700.00	270.00	75.8	0	0	345.80	
I_3 (%80)	4	1404.00	140.40	203.7	0	0	344.10	330.55
	6	2412.00	241.20	75.8	0	0	317.00	

CONCLUTION

It well be conclude that the wheat crop can give its full production capacity if spraying with silicon is coincides during the growth stages as a result of increasing the efficiency of water use. The results of the I_2 and Si_2 treatment indicated (depletion 60% of the available water and spraying silicon at a concentration of 200 mg L^{-1}), which contributed to maintaining the water balance within the plant and the response of the wheat plants to tolerate conditions of moisture depletion.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DECLARATION OF FUND

The authors declare that they have not received a fund.

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