PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7989

eISSN 2348-1900

RESEARCH ARTICLE

Synergistic effects of water management and silicon on barley growth and yield under agro-climatic conditions of Punjab, India

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Received: 28 February 2025; Accepted: 06 May 2025; Available online: Version 1.0: 17 May 2025

Cite this article: Saumya S, Hitesh K, Dipak G, Mayur D. Synergistic effects of water management and silicon on barley growth and yield under agro-climatic conditions of Punjab, India. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.7989

Abstract

Climate change manifests itself in various ways, including drought, which is a worldwide phenomenon. The rising frequency and intensity of drought stress have emerged as significant threats to agricultural productivity worldwide. Water shortages during critical growth stages hinder crop productivity and production, significantly impacting global food security. Drought-induced stress disrupts plant metabolic processes, leading to reduced biomass accumulation and grain formation. Silicon (Si) has been widely recognized for its ability to enhance plant resilience under both normal and stressful conditions by improving physiological, biochemical and morphological traits. This study evaluates the role of irrigation and foliar silicon application in improving barley (*Hordeum vulgare* L.) growth, yield attributes and biochemical responses. The findings reveal significant effects of irrigation and silicon treatments, highlighting their role in mitigating drought-induced stress. Among the treatments, four irrigations (I_3) significantly improved morphological traits, yield attributes and yield and biochemical parameters of barley. Additionally, foliar silicon application at 0.5 % demonstrated a notable ameliorate effect on plant growth, yield attributes and relative water content. Silicon supplementation helps to improve osmotic balance, enzyme activity and defense mechanisms, which could possibly play a crucial role in enhancing drought tolerance. Multivariate analyses, including principal component analysis, identified key variables distinguishing treatment responses under drought stress. Furthermore, classification based on stress tolerance indices provided insights into the effectiveness of different silicon levels in enhancing drought resistance. These findings highlight the potential of integrating irrigation management with silicon supplementation to enhance barley's adaptation to drought stress, offering valuable implications for sustainable crop production in arid and water-limited agroecosystems. An overdose of foliar silicon negatively impacted my barley crop by reducing growth and yield due to potential nutrient imbalances and physiological stress.

Keywords: barley; drought; irrigation levels; silicon; stress

Introduction

Barley (*Hordeum vulgare* L.) is the 4th major cereal crop, after wheat, rice and corn throughout the globe with a share of about 7 % of the global cereals production and 15 % of coarse grains consumption, reflecting a production of 1.91 million tonnes in India and 142.2 million tonnes globally (1). Barley having great adaptability, can grow in all three regions of the world including the temperate, tropical and subtropical, even in the presence of adverse climatic conditions like drought, salinity and alkalinity (2). In India, a significant amount of the barley cultivated is utilized for industrial uses such as the manufacturing of beer and whiskey, as well as animal feed (3). Sustainable agriculture is severely hampered by the limited water supplies in arid and semi-arid areas; by 2025, drought stress is expected to adversely affect 30 % of the arable land (4).

Water being the most vital natural resource on earth, that is essential for agriculture and advancing civilizations in the modern world. One of the most important inputs for agricultural output is regarded to be water (5). It facilitates a higher productive potential from the land and significant response from applied agricultural inputs *viz*., high yielding varieties and fertilizer etc. In various climatic situations, the primary impediment to plant growth and development is water stress during the key growth period (6). Artificially watering of plants is one of the most important technique for enhancing production. For a plant to develop properly in terms of vegetative and reproductive growth, there must be sufficient soil moisture (7). Drought stress affects several physiological and biochemical processes, especially during crucial growth phases certainly early tillering, flag leaf emergence and grain filling stage, which in turn affects barley growth and production (5). This further leads to stomatal closure, which decreases the pace at which photosynthesis transpired and the amount of CO_2 assimilates (8).

Silicon is the second most abundant element in the world after oxygen (9) and it makes up 31 % of total soil mass (10). Silicic acid is the most available form of silicon found in soils (11). In agriculture, silicon is often utilized as fertilizer with the aim of elevating yield, resistance to disease and insect-pest as well as tolerance to abiotic stresses such as cold, drought and toxic metals (12). Wheat, paddy, cucurbits, turf grass, corn and sugarcane have been shown to benefit through silicon fertilization (13). The application of nano-fertilizers, specifically silicon-containing ones can improve crop productivity and provide a sustainable solution for agriculture in water-stressed areas. It can also reduce environmental pollution, improve nutrient efficiency and mitigate the negative effects of excessive fertilization (14). The optimal amount of silicon is required for cell development and differentiation (15). In barley, silicon is reported to be used successfully as a plant mitigation strategy in low-moisture environments (16). Even though silicon is found in soil everywhere, it has been proven that higher plants require it; plants that lack silicon develop abnormally in comparison to those that have silicon supplements (17). It provides resistance to environmental stresses by fortifying cell walls and triggering defense mechanisms, which protects barley quality and yield in unfavorable growth environments (18). Furthermore, it has been discovered that silicon benefits plants by reducing the effects of biotic and abiotic stressors such salt, drought, heavy metal toxicity and high temperatures (4). However, silicon appears to be superfluous during vegetative growth, but when applied under adverse conditions, it promotes the growth of the *gramineae* family (19). Moreover, silicon utilization might lessen the requirement for irrigation, which helps keep the soil from being salinized. To encourage environmentally sound and sustainable agriculture practices, silicon fertilizer is regarded as an exceptional choice. Considering all the preceding research and future challenges, it was hypothesized that exogenous silicon treatment might lessen the unfavorable effects of water stress on the plant physiological characteristics and growth.

Materials and Methods

Experimental site and soil properties

The variety of barley used in the experiments was PL891 which was released by Punjab Agricultural University (PAU) Ludhiana, Punjab. The variety has a growth period of approximately 144 days (timely sown). The current investigation was carried out in *Rabi* 2023-2024 in the experimental area of Agricultural Research Field, School of Agriculture, Lovely Professional University, Phagwara (Punjab). In terms of geography, Lovely Professional University is situated at 31° 13' 28'' North latitude and 75° 46' 25'' East longitude, with an elevation of 245 m Above Mean Sea Level (AMSL) having a subtropical climate (Fig. 1). The International Society of Soil Science (ISSS) approved triangle method of soil classification suggests that the soil in the experimental field may texturally be classified as sandy loam.

Experimental design and treatment details

Split Plot Design (SPD) with three replications was used to allocate the treatments. The treatments were arranged randomly within each replication, into 45 plots. The variables included three levels of irrigation *viz.* I_1: Control (no irrigation), I_2: two irrigations (tillering + grain development stage) and I_3: four irrigations (tillering + jointing + boot + grain development stage); along with five levels of foliar silicon application *viz.* Si_1: 0 % (control, water spray with 0 % Si), Si_2: 0.5 % (tillering stage), Si_3: 0.5 % (tillering + booting stage), Si_4: 1 % (tillering stage), Si_5: 1 % (tillering + booting stage). Data were recorded for four different parameters like morphological (plant height (cm), leaf area index (LAI) (m^{-1} row length), number of total tillers and effective tillers at physiological maturity (m^{-1} row length) and dry matter accumulation (g $plant^{-1}$)); yield attributes like number of spikelets $spike^{-1}$, number of grains $spike^{-1}$, spike length (cm), 1000-grain weight (g), grain yield (qha^{-1}), straw yield (qha^{-1}) and harvest index (%); biochemical parameters like SPAD chlorophyll index (60 DAS) and proline content (60 DAS) (µmol/g fresh wt.) and plant water relation like Relative Water Content (%) at 60 DAS.

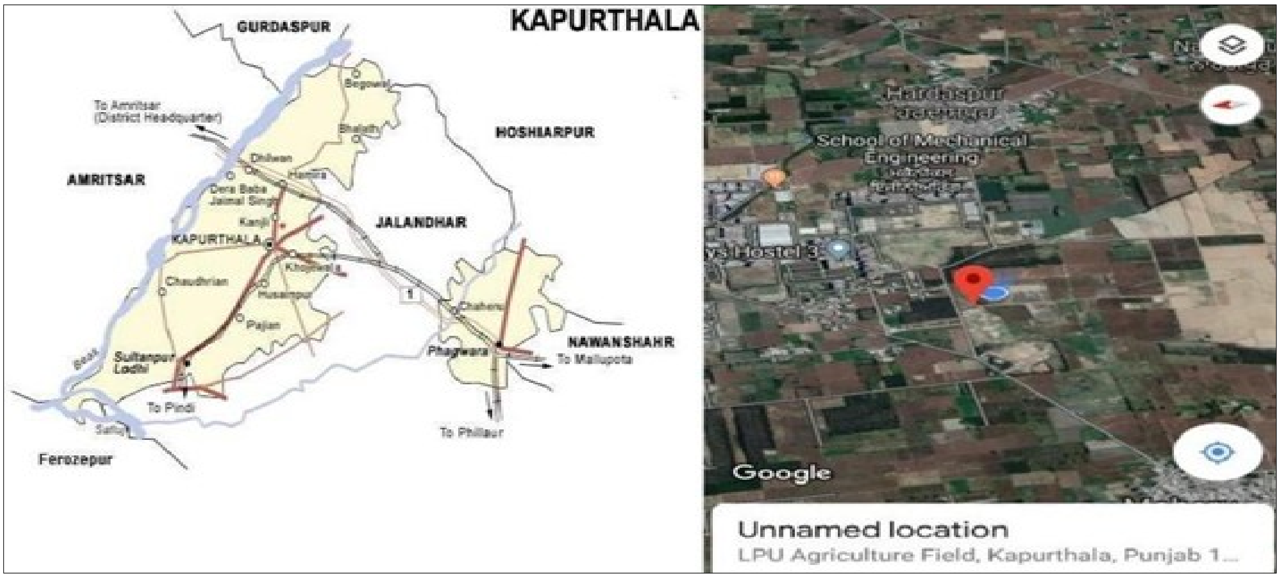

Fig. 1. LPU Agriculture Field, Kapurthala, Punjab.

Source and preparation of silicon solution

Kaolinite based greensil silicon in powdered form having 95 % silica compound and water dissolvable was used as a source of silicon for foliar spray. 0.5 % silicon solution was prepared by dissolving 0.5 g of silicon powder in 100 mL of water, similarly 1 % silicon solution was prepared by dissolving 1 g of powdered greensil in 100 mL of water.

Studied parameters

Morphological parameters

Plant height (cm) was recorded from the base to the tip of the highest plant part. It was measured with the help of measuring tape and calculated by taking average height of five tagged plants from each of the three replications of each treatment. The leaves were plucked and separated from the lamina.

The LAI was measured by using leaf area meter.

$$\text{LAI} = \frac{\text{Total leaf area (cm}^2\text{)}}{\text{Ground area (cm}^2\text{)}}$$

The total and effective tillers were recorded from five selected one-meter row lengths within each plot and the average number of total and effective tillers per meter row length was then calculated for statistical analysis.

The plant dry matter accumulation includes all its solid constituents except water. It was measured in grams per plant by uprooting entire plants, followed by air drying and subsequent oven drying at 65 °C for three days. It was recorded as the average weight of five randomly selected plants from each of the three replications per treatment.

Yield contributing characters

The total number of spikelets per spike was recorded in each plot. The mean value was determined based on observations from five randomly selected plants.

Five productive spikes at harvest from each treatment plot were threshed, cleaned and analyzed. The number of grains per spike was counted and the average grain count per spike was estimated.

Five productive spikes were selected from each plot at physiological maturity. The length of each spike was measured from its base to the tip of the uppermost spikelet (excluding awns) using a measuring scale and the average spike length (cm) was determined for each treatment.

Grains obtained from each treatment were cleaned and sun-dried to a uniform moisture level. A random sample of 1000 grains were weighed using a precision balance and the 1000 grain weight (g per 1000 grains) was recorded for each treatment.

The harvested produce from each plot was dried for 3 - 4 days and the total weight was recorded as biological yield. Threshing was done manually to obtain grain yield, while straw yield was determined by subtracting grain yield from biological yield. The final yields were expressed in qha^{-1}.

Harvest index was calculated as the ratio of economic yield (grain yield) to biological yield and expressed as a percentage. It was determined using the formula:

$$\text{Harvest index} = \frac{\text{Grain yield (qha}^{-1}\text{)}}{\text{Biological yield (qha}^{-1}\text{)}} \times 100$$

Biochemical parameters and Relative Water Content (RWC)

To determine the leaf chlorophyll concentration (SPAD value), data was taken using a chlorophyll meter (Minolta SPAD-502 Plus). Five plants per treatment were chosen and the completely developed leaves (the youngest fully expanded leaf) were counted from the top of the plants to record the SPAD (Soil Plant Analysis Development) values.

Proline content in leaves was estimated following the standard procedure (20) from five randomly selected plants in each plot.

The following formula was used to determine relative water content, which is the ratio of actual water content to water content at saturation and is given as a percentage:

$$\text{RWC} = \frac{\text{Fresh weight- Dry weight}}{\text{Saturated weight- Dry weight of leaf}} \times 100$$

Statistical analysis

The incurred data from the current research trial at different growth stages of barley was subjected to Analysis of Variance (ANOVA) at 95 % confidence level (5 % level of significance; $p \leq 0.05$) to test for the significant variation in different morphological as well as yield contributing characters using IBM SPSS (version 26; SPSS Inc., Chicago, IL, USA).

Results

Morphological characters

The morphological parameters studied included plant height, LAI, number of total tillers, number of effective tillers and dry matter accumulation. The effects of irrigation and foliar silicon application and their interaction significantly influenced all traits ($p < 0.05$) (Table 1, Fig. 2).

Plant height exhibited a significant upward trend with irrigation and silicon application ($p<0.05$). Compared to I_1, treatment I_2 and I_3 resulted in an increase of 16.3 % and 25.7 % respectively ($p<0.05$), reflecting enhanced water availability. Among silicon treatments, Si_3 improved plant height by 22.8 % compared to Si_1 suggesting a beneficial role of silicon in structural development whereas Si_4 and Si_5 were found statistically at par ($p<0.05$).

LAI responded significantly to irrigation and silicon supplementation ($p<0.05$). Increase in irrigation from I_1 to I_2 and I_3 resulted in an improvement of 17.1 % and 22.9 % respectively ($p<0.05$), indicating restricted leaf expansion under reduced water supply. Among silicon treatments Si_3 led to a 17.6 % higher LAI compared to Si_1 ($p<0.05$). These variations highlight the contribution of both factors in maintaining leaf turgidity and expansion.

Tillering potential was significantly influenced by irrigation and silicon application ($p<0.05$). Irrigation at I_2 increased the total tiller count by 24.7 % over I_1, while I_3

Table 1. Effect of irrigation levels and silicon on morphological parameters of barley

Treatments	Plant height (cm)	Leaf Area Index (LAI)	Number of total tillers	Number of effective tillers	Dry matter accumulation (g plant^{-1})
Main plot: Irrigation levels (I)					
I_1	75.72±9.45^c	3.10±0.24^c	71.51±5.90^c	57.82±6.24^c	38.60±4.89^c
I_2	88.13±4.02^b	3.63±0.20^b	89.18±10.26^b	79.36±8.56^b	48.66±3.20^b
I_3	95.25±8.82^a	3.81±0.30^a	95.47±7.86^a	86.75±12.42^a	56.98±6.44^a
SE(m)±	0.42	0.02	0.33	0.34	0.45
CD at 5%	1.70	0.08	1.31	1.37	1.82
Sub plot: Foliar silicon (Si)					
Si_1	77.05±7.93^d	3.18±0.32^d	74.07±9.22^e	62.18±8.68^e	43.06±5.75^d
Si_2	90.32±8.10^b	3.64±0.35^b	90.41±11.15^b	80.04±12.19^b	50.07±7.46^b
Si_3	94.69±7.71^a	3.74±0.45^a	95.45±13.04^a	85.96±16.62^a	53.67±10.47^a
Si_4	84.01±16.13^c	3.52±0.38^{bc}	85.70±10.07^c	74.92±13.92^c	47.82±6.96^c
Si_5	85.75±6.28^c	3.47±0.34^c	81.30±12.08^d	70.11±15.10^d	45.79±11.38^c
SEm±	0.71	0.04	0.52	0.59	0.70
CD at 5%	2.05	0.12	1.53	1.74	2.06
Interaction (I X Si)					
I at Si					
SE(m)±	1.16	0.06	0.87	0.98	1.18
CD at 5%	3.57	0.19	2.69	3.00	3.64
Si at I					
SE(m)±	0.94	0.04	0.73	0.76	1.01
CD at 5%	3.72	0.20	2.78	3.14	3.76

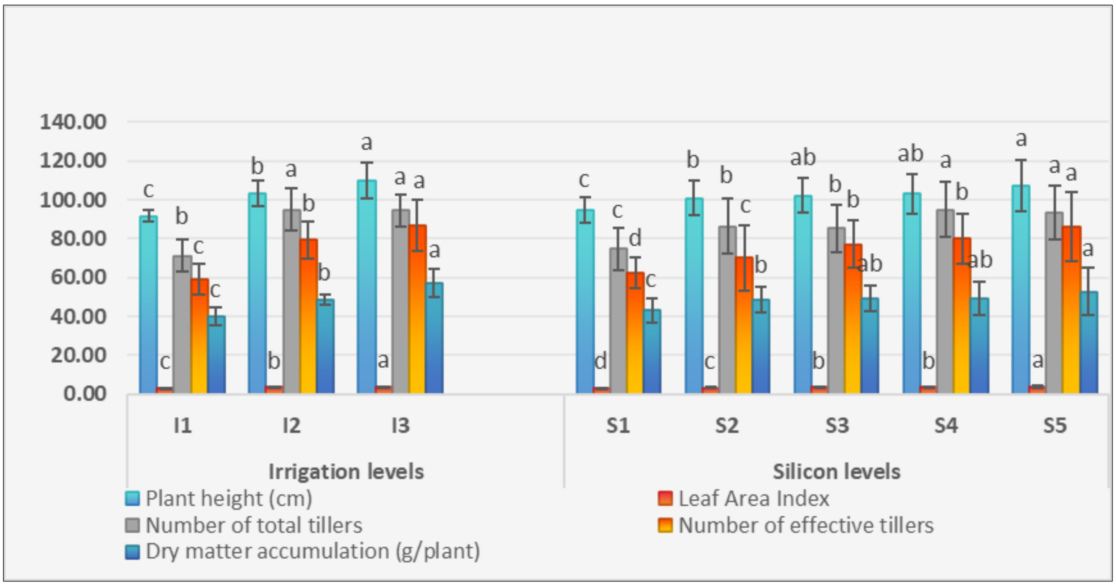

Fig. 2. Effect of irrigation levels and silicon on morphological parameters of barley.

further improved it by 33.4 % ($p<0.05$) aligning with optimal moisture conditions. Among silicon treatments, Si_3 produced 28.9 % more total tillers than Si_1, whereas Si_4 resulted in significantly fewer tillers than Si_3 but remained superior to Si_1 ($p<0.05$). Effective tiller formation followed a comparable pattern where irrigation at I_2 and I_3 increased the effective tiller count by 37.2 % and 50.0 %, respectively, compared to I_1 ($p<0.05$). Among silicon treatments, Si_3 increased the number of effective tillers by 38.3 % over Si_1, demonstrating superior tiller survival rates, suggesting a direct link between resource availability and productive tiller formation, while Si_4 showed a significantly lower count than Si_3 ($p<0.05$).

Dry matter accumulation varied significantly across treatments ($p<0.05$). Compared to I_1, irrigation at I_2 and I_3 enhanced dry matter accumulation by 26.1 % and 47.6 %, respectively ($p<0.05$), supporting the idea that ample moisture facilitates biomass production. Among silicon treatments, Si_3 resulted in a 24.7 % increase in dry matter accumulation over Si_1, reinforcing the positive influence of silicon on plant vigor while Si_4 and Si_5 remained statistically at par ($p<0.05$).

The interaction between irrigation and foliar silicon was statistically significant ($p\leq0.05$) for all morphological parameters. The interactive effect of $I_3 \times Si_3$ resulted in the highest plant height, LAI, tiller number and dry matter accumulation, indicating a synergistic effect of optimal irrigation and silicon application, whereas combination of $I_1 \times Si_1$ recorded the lowest values.

Yield contributing characters

The yield-contributing traits of barley exhibited significant responses to different irrigation and foliar silicon applications (Table 2, Fig. 3).

The number of spikelets per spike varied significantly across treatments ($p<0.05$). Increasing irrigation from I_1 to I_2 and I_3 led to an improvement of 41.5 % and 61.3 %, respectively. Among silicon treatments, Si_3 exhibited the highest number of spikelets, showing a 37.1% enhancement over Si_1.

Irrigation and silicon application significantly affected the number of grains per spike ($p<0.05$). Grain count improved by 22.7 % under I_2 and 44.2 % under I_3 compared to I_1. Among silicon levels, Si_3 showed a notable enhancement of

30.2 % over Si_1.

Spike length responded significantly to irrigation and silicon supplementation ($p<0.05$). Compared to I_1, irrigation at I_2 and I_3 increased spike length by 35.7 % and 36.9 %, respectively, highlighting the substantial impact of improved water availability. Among silicon treatments, Si_3 led to a 25.3 % increase over Si_1.

The 1000 grain weight was significantly affected by irrigation and silicon application ($p<0.05$). Irrigation treatments showed an increase of 24.5 % under I_2 and 29.9 % under I_3 compared to I_1. Silicon application at Si_3 resulted in a 16.2 % improvement over Si_1.

Grain yield exhibited a significant response to irrigation and silicon application ($p<0.05$). Compared to I_1, grain yield increased by 56.4 % and 75.3 % under I_2 and I_3 respectively. Among silicon treatments, Si_3 enhanced grain yield by 41.7 % compared to Si_1.

Straw yield was significantly affected by irrigation and silicon application ($p<0.05$). The application of I_2 and I_3 led to a rise in straw yield of 29.2 % and 38.9 % respectively, over I_1. Foliar silicon application at Si_3 resulted in a 29.6 % enhancement, significantly outperforming Si_1.

Harvest index was significantly influenced by irrigation and silicon application ($p<0.05$). A shift from I_1 to I_2 and I_3 resulted in an increase of 13.5 % and 16.2 %, respectively. Among silicon treatments, Si_3 recorded a 15.8 % improvement over Si_1.

The interaction effect of irrigation and silicon was statistically significant ($p<0.05$) for grain yield, straw yield and spikelet number, indicating that the combined application of higher irrigation and silicon enhanced these parameters more effectively than individual treatments. However, for

Table 2. Effect of irrigation levels and silicon on yield contributing characters of barley

Treatments	Number of spikelets spike^{-1}	Number of grains spike^{-1}	Spike length (cm)	grain weight (g)	Grain yield(qha^{-1})	Straw yield (qha^{-1})	Harvest index (%)
Main plot: Irrigation levels (I)							
I_1	15.05± 2.99^{c}	33.13±3.29^{c}	6.70±1.27^{b}	31.38±5.23^{c}	21.88±6.09^{c}	37.03±7.05^{c}	36.67±4.01^{b}
I_2	21.28±1.71^{b}	40.67±6.81^{b}	9.09±0.55^{a}	39.00±1.65^{b}	34.22±3.15^{b}	47.96±3.34^{b}	41.62±2.39^{a}
I_3	24.27±3.33^{a}	47.76±4.07^{a}	9.17±0.98^{a}	40.95±2.55^{a}	38.34±4.01^{a}	51.61±5.17^{a}	42.62±1.54^{a}
SE(m)±	0.26	0.36	0.10	0.40	0.44	0.53	0.49
CD at 5%	1.07	1.44	0.39	1.59	1.77	2.14	1.93
Sub plot: Foliar silicon (Si)							
Si_1	17.31 ± 3.50^{d}	35.42 ± 5.94^{d}	7.35±1.79^{c}	34.49±6.39^{b}	25.92±8.70^{d}	39.42±8.04^{d}	38.62±3.07^{b}
Si_2	21.27 ± 3.85^{b}	43.53 ± 6.97^{b}	8.93±1.23^{a}	38.92±3.34^{a}	34.12±5.56^{b}	48.12±4.33^{b}	41.29±2.48^{ab}
Si_3	23.64 ± 4.46^{a}	46.13 ± 6.89^{a}	9.21±0.99^{a}	40.19±2.95^{a}	36.75±6.33^{a}	51.11±7.00^{a}	41.73±2.60^{a}
Si_4	19.69 ± 3.52^{c}	39.53 ± 7.54^{c}	8.13±1.91^{b}	36.46±6.32^{b}	30.82±8.92^{c}	44.96±6.36^{c}	39.93±4.65^{ab}
Si_5	19.09 ± 6.17^{c}	37.98 ± 7.63^{c}	7.97±0.73^{bc}	35.49±5.82^{b}	29.79±9.05^{c}	44.07±10.43^{c}	39.94±3.64^{ab}
SEm±	0.42	0.74	0.22	0.68	0.78	0.85	0.87
CD at 5%	1.24	2.18	0.63	2.00	2.30	2.50	2.54
Interaction (I X Si)							
I at Si							
SE(m)±	0.69	1.20	0.35	1.13	1.29	1.42	1.44
CD at 5%	2.13	3.64	NS	3.45	3.96	4.38	NS
Si at I							
SE(m)±	0.55	0.80	0.22	0.89	0.98	1.19	1.10
CD at 5%	2.22	3.89	NS	3.61	4.16	4.55	NS

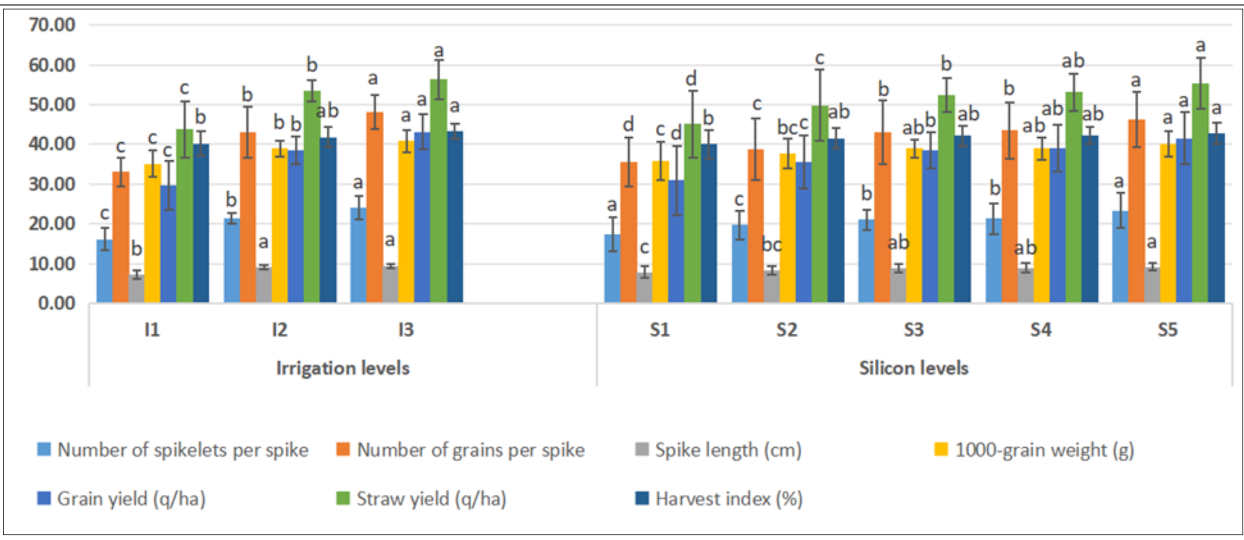

Fig. 3. Effect of irrigation levels and silicon on yield contributing characters of barley.

spike length, 1000 grain weight and harvest index, the interaction remained non-significant, suggesting that their improvement was primarily driven by independent contributions of irrigation and silicon rather than their combined influence.

Biochemical parameters and Relative Water Content (RWC)

The impact of irrigation and foliar silicon application on SPAD values, proline content and RWC exhibited significant variations (Table 3, Fig. 4).

SPAD values exhibited a significant increase with irrigation and foliar silicon application ($p<0.05$). Compared to I_1, irrigation at I_2 and I_3 improved SPAD by 14.9 % and 20.5 %, respectively, indicating enhanced chlorophyll retention under higher moisture availability. Among silicon treatments, Si_3 recorded the highest SPAD value, which was significantly 18.2 % higher than Si_1 ($p<0.05$), suggesting silicon's role in improving chlorophyll stability. However, Si_2 and Si_3 were found to be statistically at par with each other, exhibiting no significant difference. Similarly Si_4 and Si_5 did not differ significantly and were statistically at par ($p<0.05$).

Proline content significantly decreased with increased irrigation levels ($p<0.05$). Compared to I_1, irrigation at I_2 and I_3 reduced proline accumulation by 8.6 % and 13.9 %, respectively, indicating that moisture stress led to higher proline biosynthesis. Among silicon treatments, Si_3 recorded the lowest proline content, showing an 11.6 % reduction compared to Si_1, suggesting silicon-mediated stress alleviation. Although Si_3 exhibited the lowest value, it was statistically at par with Si_4 ($p<0.05$), indicating no significant difference between them.

RWC (%) significantly improved with irrigation and silicon supplementation ($p<0.05$). Compared to I_1, irrigation at I_2 and I_3 increased RWC by 13.1 % and 16.7 %, respectively ($p<0.05$), reflecting better plant hydration under sufficient moisture conditions. Among silicon treatments, Si_3 showed the highest RWC, which was 17.9 % higher than Si_1 ($p<0.05$), confirming silicon's role in maintaining cellular water status.

The interaction between irrigation and foliar silicon application was statistically significant ($p<0.05$) for SPAD index, while it was non-significant for proline content and RWC. The highest SPAD, RWC and lowest proline accumulation were observed under the $I_3 \times Si_3$ combination, demonstrating a synergistic effect of optimal irrigation and silicon application in reducing stress and improving plant biochemical status. Conversely, $I_1 \times Si_1$ recorded the lowest SPAD and RWC while exhibiting the highest proline content.

Table 3. Effect of irrigation levels and silicon on biochemical parameters and on RWC of barley

Treatments	SPAD	Proline content (µmol/g fresh wt)	Relative water content (%)
		Main plot: Irrigation levels (I)	
I_1	39.10±5.57^{c}	10.18±0.49^{a}	53.96±5.62^{b}
I_2	44.97±1.83^{b}	9.32±0.42^{b}	61.03±3.20^{a}
I_3	47.11±2.53^{a}	8.75±0.62^{c}	62.95±4.32^{a}
SE(m)±	0.37	0.06	0.59
CD at 5%	1.48	0.25	2.39
		Sub plot: Foliar silicon (Si)	
Si_1	39.90±6.72^{c}	9.93±0.43^{a}	53.51±6.04^{d}
Si_2	45.83±2.50^{a}	9.44±0.77^{b}	61.85±2.88^{ab}
Si_3	47.12±3.14^{a}	8.91±0.78^{c}	63.14±4.27^{a}
Si_4	42.92±4.73^{b}	9.35±0.84^{c}	59.44±6.53^{bc}
Si_5	42.86±4.04^{b}	9.44±0.80^{b}	58.61±4.70^{c}
SEm±	0.59	0.13	0.92
CD at 5%	1.73	0.39	2.69
		Interaction (I X Si)	
		I at Si	
SE(m)±	0.99	0.21	1.54
CD at 5%	3.04	NS	NS
		Si at I	
SE(m)±	0.82	0.14	1.33
CD at 5%	3.16	NS	NS

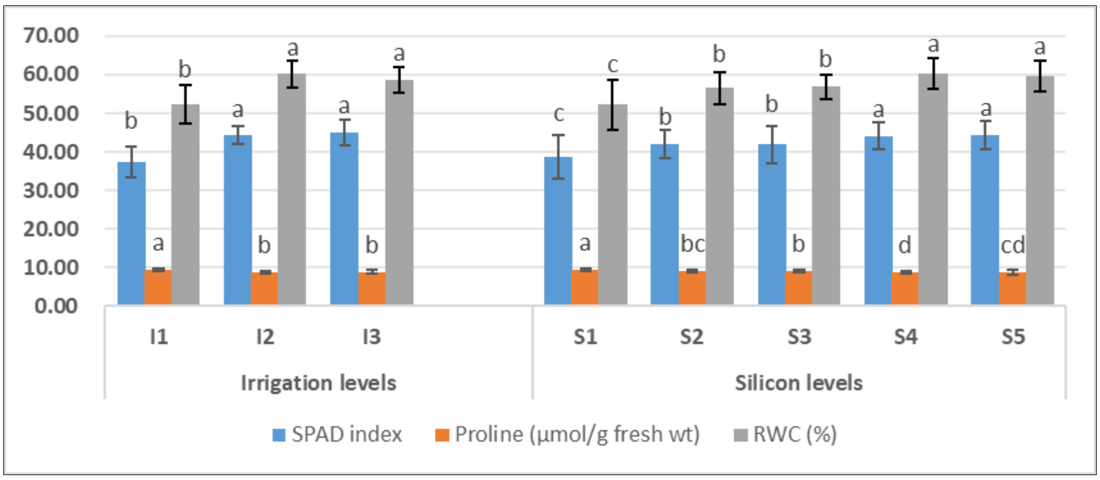

Fig. 4. Effect of irrigation levels and silicon on biochemical parameters and on RWC of barley.

Discussion

Morphological parameters

The production and growth of plants were significantly reduced by drought (21). Reduced water absorption and vascular tissue shrinkage may result from low water abundance in the root zone (22). Drought prevents plants from absorbing nutrients and produces Reactive Oxygen Species (ROS), which leads to oxidative damage and a decline in plant development (23). The enhanced moisture availability results in greater nutrient use and higher rates of cell division and elongation which results in improved plant height (24). The deposition of silicon in the cell walls of plants treated with silicon increases stem and leaf erectness resulting in increased plant height (25).

The watered plants increased leaf expansion was the cause of the rise in leaf area index (26). Increased turgor pressure in the cells because of increased soil moisture contributed to the process of leaf expansion, due to turgor forces (27). Previous experiments conducted with silicon have reported where silicon treatment can maintain leaf area when compared to the untreated plants grown under drought conditions (28). Additionally, crops treated with silicon have demonstrated higher leaf area index values than crops grown without silicon (29).

Since the number of tillers affects the number of spikelets that bear grain, it is regarded as a significant yield characteristic. The field's consistent moisture level preserved several metabolic processes that resulted in abundant tillering (30). It has been confirmed that inadequate fertilization under water stress led to a reduction in the number of tillers (31). Furthermore, productive tillers showed a favorable correlation with both grain and biological yield. Water stress can therefore impact physiological maturity throughout both reproductive and vegetative phases by slowing the growth and development of productive tillers (19). The silicon supplementation could enhance the tiller number as compared to control in rice (25). Increase in tiller number in case of silicon fertilized plants was also reported in early works (32-34).

Since water makes up the majority of protoplasm, more water is needed to keep cells turgor intact and leaves completely extended. In these circumstances, plants photosynthesize more, which results in increased dry matter accumulation. Improved plant growth resulting in increased dry mass accumulation may be attributed to increased nutrient absorption and water retention (25) and increased cell division and elongation in the presence of high availability of moisture and high rates of photosynthesis (24). Lowest dry matter accumulation might be the consequence of inadequate hydration, which led to decreased photosynthetic activity, plant height, tiller count and leaf area (35). The pace of phloem translocation, photosynthetic accumulation and other critical components that cause dry matter accumulation in plants may be impacted by the increase in dry matter accumulation brought on by the application of silicon (36).

Yield contributing characters

Drought and other stressful situations have a negative impact on spikelet growth (37). When there is reduced water stress, the plants more effectively allocate resources to reproductive structures, such as the formation of more spikelets (38). A plant's capacity to sustain healthy pollen and enable efficient pollination can be improved by adequate water availability and this can lead to the formation of more spikelets (39). Application of silicon enhanced the amount of dry matter and carbohydrates generated (40), which in turn increased the total number of spikelets spike^{-1}. Rice experiments confirmed that, under drought conditions, the number of spikelets panicle^{-1} was lower to well-watered settings (25). Application of silicon to the plants helps to reduce the decline in the number of spikelets panicle^{-1} in rice (41).

Barley produces more grains when it is regularly irrigated because it lowers water stress and promotes healthier plant development (5). Adequate moisture enhances nutrient uptake and prolongs reproductive phase, allowing grains to mature better, hence more grains spike^{-1} (42). Similar results were reported in wheat and reported that with the increasing irrigation levels, number of grains spike^{-1} enhanced (43). Additionally, it has been found that silicon helps stressed rice plants retain more of their filled grains and promotes the erectness of their leaves, which in turn reduces self-shading and increases photosynthesis, especially during the grain filling phase when starch builds up in the grains (44). One reason for an elevated quantity of grains may be the effectiveness of silicon fertilizers in promoting the digestion of carbohydrates in panicles. Additionally, silicon plays a critical role in increasing the grain count of rice (40).

Irrigation extends spikes and fosters optimal plant growth and development by providing consistent moisture (45). Adequate water boosts nutrient absorption and reduces stress, promoting stronger and healthier surges, leading to longer spikes (37). These outcomes were consistent with previous works (46). Silicon supports and aids in the development of barley by enhancing the plant's structural integrity and cell wall strength (47). By promoting photosynthesis and nutrition absorption, it lengthens spikes. Moreover, silicon promotes longer, healthier spikes by strengthening the plant's resistance to stress (48).

Higher soil and plant moisture made it easy for food to move from source to sink, which results in a higher 1000 grain weight (43). Increase in 1000 grain weight for silicon treatments due to involvement of various macro and micro components in grain husk, increased photosynthetic activity, starch synthesis and dry matter (36).

Increased irrigation levels may result in better grain production since the root zone is sufficiently wet during the crop's growth phase owing to relative soil moisture stress at crucial phases (49). Net photosynthesis is lowered owing to an increase in the rate of photorespiration, which decreased wheat grain production in the absence of irrigation scheduling (43). Since spike number per unit area is directly correlated with tillering capacity, it is well recognized that tillering capacity affects grain yield. The increase in grain yield may be attributed to silicon's beneficial effects on growth and yield characteristics, which include boosting photosynthetic activity and pollen viability, reducing biotic and abiotic stress, enhancing structural support and biomass and enhancing nutrient uptake (50).

Water conservation in the root zone during the grain filling stage helps to increase the straw yield (43). By fortifying plant cell walls and improving structural integrity, silicon increases straw output by reducing lodging (51). Additionally, silicon improves water and nutrient intake, which fosters greater development as well as improves the resistance towards environmental stress (52).

The source-sink link may be improved by having the most beneficial soil moisture available after four irrigations, enabling a larger transfer of photosynthetic chemicals from leaves to grain and increasing crop output. On the other hand, crop moisture stress brought on by a lack of water can reduce the amount of carbohydrates and growth chemicals that are translocated, disrupt nitrogen metabolism, drive turgor loss and ultimately reduce the size and growth potential of the sink (53). Moreover, the decline in the harvest index during dry circumstances might be due to leaf abscission, which can cause a reduced biological output (37). Applying silicon greatly boosted yield and yield characteristics like harvest index, which may have been caused by the crop's increased photosynthetic activity (54). A statistically significant rise in the harvest index when exogenous silicon was applied (55).

Biochemical parameters and Relative Water Content (RWC)

The reduction in SPAD content may be facilitated by the absence of irrigation or watering, elevated concentrations of peroxidase and chlorophillase enzymes and reactive oxygen species (increases in O_2 and H_2O_2), which cause lipid peroxidation and a subsequent decrease in chlorophyll content (24). The value recorded from a SPAD meter is used as an indicator of how relative chlorophyll concentration reacts to various stimuli, such as moisture and extremely high or low temperatures. The impact of drought stress on chlorophyll degradation is the cause of the decrease in chlorophyll concentration under dry circumstances. Due to the disruption of the photosynthetic pigments (chlorophyll a, chlorophyll b and total pigments) caused by drought stress, the photosynthetic system suffers irreparable damage, which lowers gas exchange and stunts plant growth and production (43). Silicon use promotes improvements in plant structure, which may also increase photosynthesis (56). Silicon application increased chlorophyll is related to silicon accumulation in epidermal cells located in the shoot (57), which indirectly shields the photosynthetic apparatus and lessens the extent of damage caused by a reduction when considering this attribute (25). Similar findings of lower chlorophyll content when irrigation was stopped (58, 59).

Heterocyclic amino acid - proline has been shown to accumulate in the cytoplasm of cells and is known to be associated with proteins. It is thought to be one of the several significant compatible solutes that build up during stressful circumstances and significantly contribute to osmotic adjustment. Few studies have looked at elevated proline levels as a sign of damage rather than a factor in stress tolerance. Proline functions as an osmolyte as well as an electron sink, radical scavenger and macromolecule stabilizer (25). It is known to accumulate in plants as a response to water stress. When plants experience drought or insufficient irrigation, proline levels often increase (60). This accumulation helps the plant cope with osmotic stress by acting as an osmoprotectant, stabilizing proteins and cellular structures (61). Adequate irrigation helps to maintain better hydration and overall health of the plant and thereby reducing the need for proline as a stress response mechanism (62). The reduction in proline levels in stressed plants caused by silicon supplementation may indicate the lessening of stress-related damage. Under stress, rice proline concentration was found to decrease with silicon supplementation (63).

It has been shown that the RWC is a useful screening technique for drought resistance in cereals and a reliable indication of the water status of plants in relation to their completely turgid state. RWC helps to stabilize grain yields during drought (3). Water stress reduces the relative water content of crops by inducing water loss, increasing the buildup of harmful ions that damage cell membranes and hamper metabolic activities. Turgor loss in leaves is a result of these effects. On the other hand, irrigation keeps relative leaf water content and high turgor pressure (24). The ability of silicon to maintain the RWC under water stress is a significant property. Water stress decreased the plant body's relative water content and nutrient absorption; however, Si treatment worked miraculously and kept the turgor pressure intact, promoting increased plant growth and production (19).

Conclusion

From results it is concluded that both irrigation practices and foliar silicon applications significantly influence barley growth and yield. The results indicate that optimized irrigation schedules along with appropriate foliar application of silicon can maximize growth parameters, like plant height, leaf area index, number of effective tillers, dry matter accumulation, number of spikelets, number of grains, 1000 grain weight, grain yield, straw yield, harvest index. These findings underscore the importance of integrated management strategies that leverage both water and nutrient inputs to achieve sustainable barley production. Future research should focus on fine-tuning these practices across different environmental conditions and exploring the underlying mechanisms through which silicon enhances stress resilience. Ultimately, adopting such approaches could offer practical solutions for enhancing barley productivity and sustainability in diverse agricultural settings.

Acknowledgements

I would like to express my profound sense of gratitude towards Lovely Professional University, Punjab, where my research trial was conducted and all requirements for the same were fulfilled.

Authors' contributions

SS carried out the field research trial, collected the data and drafted the manuscript. HK carried out the statistical analysis. DG helped in the field research trial. MD prepared the design of study and performed the final editing.

Compliance with ethical standards

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

Ethical issues: None

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

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