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RESEARCH ARTICLE

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Effect of Irrigation Levels and Silicon on Growth and Productivity of Barley (*Hordeum vulgare* L.)

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ABSTRACT

Background: Irrigation management and silicon fertilization are critical challenges in optimizing crop performance, particularly under water stress conditions. Therefore, effective irrigation and silicon fertilization strategies are crucial for optimizing barley growth, particularly under varying environmental conditions. This study investigates the impact of varying irrigation levels and silicon application on the growth, phenology, yield attributes and quality of barley (*Hordeum vulgare* L.).

Methods: The experiment was conducted under controlled field conditions at the Agriculture Research Farm, Department of Agronomy, Lovely Professional University, Jalandhar, during the *Rabi* season of 2023-2024. It utilized a split plot design (SPD), featuring three irrigation levels based on number of irrigations: I_1 (no irrigation), I_2 (two irrigations at tillering and grain development) and I_3 (four irrigations at tillering, jointing, booting and grain development stages) and five silicon treatments: S_1 (control), S_2 (0.50% at tillering), S_3 (0.50% at tillering and booting), S_4 (1% at tillering) and S_5 (1% at tillering and booting). Observations were recorded on plant population, leaf area, days to emergence, heading, flowering, physiological maturity, weight of grains spike^{-1}, biological yield, SPAD chlorophyll index, proline content and relative water content.

Result: Results indicated that employing four irrigation treatments and 0.5% silicon spray applied at key growth stages significantly improved barley morphology, phenology, yield characteristics, biochemical attributes and plant-water relations indicating better water retention and stress tolerance. The synergistic effects of these treatments suggest that balanced irrigation coupled with silicon application can be an effective strategy for maximizing barley growth and quality in varying environmental conditions. This research offers valuable insights for agricultural practices aimed at optimizing cereal crop performance under variable water availability for effective crop management practices.

Key words: Barley, Drought, Foliar silicon, Irrigation, Stress.

INTRODUCTION

Globally, barley (*Hordeum vulgare* L.) is cultivated in both temperate and tropical climates due to its wide adaptability (Al-Hajaj *et al.,* 2022). After rice, maize and wheat, barley ranks fourth in global cereal production. The top barley-producing countries include Canada, Russia, Australia, Ukraine and Germany (Bvenura and Kambizi, 2022). In India, it serves as a staple grain during winter, especially in the western plains and is widely used as feed for livestock and poultry, as well as for human consumption (Verma *et al.,* 2022). Much of the barley grown in India also supports industrial applications, particularly in whiskey and beer production and as animal feed (Kumar *et al.,* 2018). Due to its strong resilience to harsh environmental conditions and minimal input requirements, barley is often referred to as the “poor man’s crop” (Chhokar *et al.,* 2022).

Drought stress is projected to reduce global agricultural productivity by up to 30% by 2025, posing a significant challenge to sustainable agriculture, especially in dry and semi-arid regions with limited water resources (Rajanna *et al.,* 2023). Global warming and climate instability are aggravating water scarcity for crops in many countries (Khondoker *et al.,* 2023). Among the various limiting factors in crop production, water availability is one of the most critical. In semi-arid regions, soil water deficit resulting from low precipitation and increased evapotranspiration is a major stressor for plants (Bello *et al.,* 2024). Meteorological drought-characterized by a prolonged decline in rainfall-combined with elevated evapotranspiration leads to agricultural drought (Sun *et al.,* 2023).

Water shortages induce plant stress that alters key physiological processes, such as stomatal closure and reduced growth, thereby lowering water consumption and

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ultimately reducing crop output (Wu *et al.,* 2022). Effective water management in crops like barley involves understanding how water stress impacts growth and productivity, along with continuous monitoring of plant and soil water status (Truscă *et al.,* 2023). Crop water stress, mainly caused by insufficient soil moisture, directly affects irrigation strategies, especially when roots fail to access adequate water or when transpiration rates become excessively high (Kang *et al.,* 2021). Classifying water stress as light, moderate, or severe is essential for planning irrigation efficiently and ensuring stable long-term yield (Seleiman *et al.,* 2021).

Silicon (Si), the second most abundant element in earth crust (28.8%) after the oxygen (47%) (Jain, 2025), plays an important role in various plant physiological processes (Souri *et al.,* 2021), particularly in alleviating stress caused by both abiotic and biotic factors like drought (Wade *et al.,* 2022). Since its absorption and transport rely on the transpiration stream, shifts in water availability due to climate change may hinder silicon's effectiveness in improving crop performance (Kuhla *et al.,* 2021). Therefore, it is vital to understand how future changes in rainfall patterns may affect Si absorption to fully harness its potential benefits (Thakral *et al.,* 2021). Silicon application enhances plants' drought tolerance through several mechanisms: boosting antioxidant defense systems, increasing CO_2 uptake during water stress (Bhardwaj and Kapoor, 2021), reducing transpiration by forming a cuticle-Si layer and reinforcing plant structure to prevent lodging (Wade *et al.,* 2022; Malik *et al.,* 2021). As climate change continues to threaten water availability, the use of Si to alleviate drought-induced yield losses in crops like barley is receiving increased attention (Irfan *et al.,* 2023).

MATERIALS AND METHODS

Experimental site and soil

The present study was conducted in *Rabi* season of 2023-2024 at Lovely Professional University, Phagwara (Punjab) at the experimental site of the Agricultural Research Field, Department of Agronomy, School of Agriculture. Lovely Professional University is situated 8 km from Phagwara, at an elevation of 245 meters above mean sea level (AMSL). The region has a subtropical climate and is located at 31.2560°N latitude and 75.7051°E longitude. Soil samples were randomly collected from various locations in the experimental field using a soil auger, down to a depth of 15 cm, to evaluate the fertility status and physiological and chemical characteristics of the soil. According to the triangle technique of soil classification established by the International Society of Soil Science (ISSS), the soil in the experimental field may texturally be categorized as sandy loam.

Experimental design and treatment details

The experiment was laid out in a split plot design with three replications. Within each of the 45 plots that made up each replication, the treatments were placed at random. As a result, 15 treatment combinations with irrigation levels in main plots and foliar silicon levels in sub-plots were compared. The variables under investigation comprised of three levels of irrigation : I_1: Control (no irrigation), I_2: Two irrigations (tillering + grain development stage) and I_3: Four irrigations (tillering + jointing + boot + grain development stage). Additionally, five levels of foliar silicon application were examined : S_1: 0% (control), S_2: 0.50% (tillering stage), S_3: 0.50% (tillering + booting stage), S_4: 1% (tillering stage) and S_5: 1% (tillering + booting stage). For foliar spray, powdered water-soluble kaolinite-based greensil silicon (95% silica compound) was utilized. The barley variety used was PL 891, known for its adaptability and suitability under Punjab agro-climatic conditions. The crop was sown with a row spacing of 22.5 cm. A recommended basal dose of fertilizers was applied at sowing time, consisting of 55 kg ha^{-1} of urea, 27 kg ha^{-1} of DAP and 75 kg ha^{-1} of murate of potash.

Statistical analysis

IBM SPSS version 26 was used to perform an ANOVA on barley growth data to assess the effects of treatment variables. The analysis tested various parameters at a 95% confidence level ($p \leq 0.05$) to determine significant variations in morphology, phenology, yield characteristics, biochemical attributes and plant-water relation.

RESULTS AND DISCUSSION

Morpho-phenological parameters of barley

Leaf area was significantly influenced by irrigation and silicon application ($p<0.05$). Compared to I_1 (control), I_2 and I_3 showed increases of 10.6% and 22.8%, respectively, due to improved moisture availability. Si_3 recorded the highest leaf area, with a 20.7% rise over Si_1 ($p<0.05$). A significant interaction effect was observed among irrigation and silicon levels (Table 1).

The increased leaf expansion in watered plants was the result of rise in leaf area. The process of leaf expansion was facilitated by both turgor forces and increased turgor pressure in the cells as a result of increasing soil moisture (Wang *et al.,* 2024). Previous experiments conducted with silicon have reported where in silicon treatment can maintain leaf area compared to the untreated plants grown under drought conditions (Ahsan *et al.,* 2023). Crops have also shown to have greater value of leaf area index under silicon treatment when compared to the silicon free growing conditions (Eghlima *et al.,* 2024).

Heading stage was significantly delayed with increasing irrigation ($p<0.05$). Compared to I_1, treatments I_2 and I_3 extended the time to heading by 5.8% and 9.9%, respectively. Silicon treatments showed no significant effect on days to heading (Table 1).

Days to flowering were also significantly influenced by irrigation ($p<0.05$). Irrigation at I_2 and I_3 increased the duration to flowering by 8.3% and 12.2%, respectively, compared to I1. No significant variation was observed among silicon treatments for this parameter (Table 1).

Physiological maturity showed significant differences across irrigation treatments (p<0.05). Compared to I_1, treatment I_2 extended the crop duration by 4.3%, while I_3 delayed it by 8.9%, pointing toward enhanced longevity under improved irrigation. Silicon levels, however, did not significantly influence this parameter (Table 1).

The most crucial factor in how different crops adjust to their growing conditions is phenological growth. It has been believed that the plant or a portion of the plant, has a developmental clock that is temperature-dependent and advances at a certain rate for each of the aforementioned phases (Nasir, 2022). The crop receiving constant access to moisture, which led to an increase in plant growth, might be the cause of the delay in the development of various phenological phases. Early development occurs when the plant is forced to finish its life cycle quickly due to water stress. Longer crop longevity and the longer reproductive phase of crop growth have also been recorded with increased irrigation levels (Kumar *et al.,* 2018; Zabihullah, 2020). This may be also be explained by the fact that sufficient moisture availability improved both the vegetative and reproductive phases of the plant. Stress at any stage of crop growth reduced the plant's life cycle by a few days since the plants sought to finish it as soon as possible in order to avoid or escape stressful situations (Kavita, 2021).

Yield attributing characteristics

Weight of grains per spike was significantly affected by irrigation and silicon application (p<0.05). I_2 and I_3 increased grain weight by 26.4% and 50.4%, respectively, over I_1 (1.25 g), with I_3 recording the highest (1.88 g). Silicon treatment Si_3 showed a 36.9% improvement over Si_1, with a grain weight of 1.89 g. Si_2 (1.75 g) and Si_4 (1.66 g) also showed significant gains. The I × Si interaction was significant, with I_3 × Si_3 showing the highest grain weight (Table 2).

By keeping grains at their ideal moisture levels, irrigation guarantees a sufficient supply of water for grain filling, thereby increasing grain weight. Better nutrient absorption and photosynthesis are facilitated by regular water supply, which promotes more robust grain growth. Plants are able to effectively acquire and retain more nutrients, which leads to the production of bigger and heavier grains (Tahir *et al.,* 2024). By improving the structural integrity and stress resilience of plants, silicon makes grains heavier by providing them with greater support and nutrition distribution. Enhancing photosynthetic efficiency and nutrient absorption results in enhanced grain filling efficacy. Furthermore, silicon aids in reducing stress that could otherwise restrict grain growth and weight. When comparing the non-silicon supplemented plants to the silicon-treated plants, an increase in grain weight (g) was seen and the increase was statistically significant (Das *et al.,* 2023).

Biological yield also responded significantly to treatments (p<0.05). I_3 produced the highest yield (89.95 q ha^{-1}), showing a 52.6% increase over I_1 (58.91 q ha^{-1}). Among silicon treatments, Si_3 recorded the highest

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

Treatments	Plant population (m^{-1} row length) (30 DAS)	Plant population (m^{-1} row length) (at maturity)	Leaf area (cm^{-2})	Days taken to emergence	Days taken to heading	Days taken to flowering	Days taken to physiological maturity
Main plot: Irrigation levels (I)							
I_1	24.82±1.61^a	19.78±1.90^a	348.68±26.75^c	6.48±0.63^a	82.84±4.41^c	84.03±7.58^b	127.48±5.13^c
I_2	24.93±1.92^a	21.02±2.65^a	408.75±21.96^b	6.67±0.60^a	87.67±5.60^b	91.73±6.76^a	133.29±5.91^b
I_3	25.87±2.00^a	20.51±2.22^a	428.10±34.13^a	6.21±0.78^a	91.05±3.78^a	94.28±7.61^a	138.83±5.53^a
SE(m)±	0.47	0.56	2.13	0.36	0.40	0.34	0.30
CD at 5%	NS	NS	8.59	NS	1.60	1.38	1.19
Sub plot: Foliar silicon (Si)							
Si_1	24.56±2.35^a	19.30±2.18^a	358.13±36.52^d	6.27±0.82^a	85.98±6.34^a	89.02±6.68^a	132.33±8.15^a
Si_2	24.78±1.86^a	20.85±2.99^a	409.25±28.69^{ab}	6.44±0.49^a	86.33±6.47^a	89.93±7.51^a	131.78±5.72^a
Si_3	24.93±1.77^a	21.44±2.29^a	421.13±50.97^a	6.53±0.51^a	88.98±2.81^a	90.02±12.47^a	132.47±6.10^a
Si_4	25.78±1.51^a	20.26±2.12^a	396.50±43.34^{bc}	6.56±0.89^a	88.82±4.28^a	91.67±6.45^a	133.73±6.33^a
Si_5	26.00±1.72^a	20.33±1.57^a	390.88±38.37^c	6.47±0.75^a	85.82±7.64^a	89.42±9.26^a	135.69±9.70^a
SEm±	0.48	0.67	4.48	0.21	1.48	2.40	1.77
CD at 5%	NS	NS	13.16	NS	NS	NS	NS
Interaction (I × Si)							
I at Si							
SE(m)±	0.87	1.17	7.26	0.49	2.32	3.72	2.76
CD at 5%	NS	NS	22.01	NS	NS	NS	NS
Si at I							
SE(m)±	1.06	1.26	4.77	0.81	0.89	0.77	0.66
CD at 5%	NS	NS	23.52	NS	NS	NS	NS

biological yield (87.86 q ha^{-1}), which was 34.5% more than Si_1 (65.34 q ha^{-1}). The interaction effect between irrigation and silicon levels was statistically significant (Table 2).

Leaf abscission under drought conditions can lead to a decrease in the weight of plant shoots and a reduction in biological production. The improvement in moisture supply and its positive impact on biological yield plant^{-1} were the main causes of the biological yield improvement (Nasir, 2022; Ghanem *et al.,* 2024). The outcomes matched the findings of Prem *et al.* (2024). The higher biological yield may be the result of enhanced nutritional availability in the soil, higher chlorophyll content and enhanced photosynthetic activity, all of which have a positive impact on the metabolism of carbohydrates and activate the carbon-fixing enzyme for greater photosynthesis. A sufficient amount of silicon boosts photosynthetic activity, enabling the plant to gather sufficient photosynthates and increase dry matter synthesis (Das *et al.,* 2023).

Biochemical parameters

SPAD chlorophyll index improved significantly with irrigation and silicon application (p<0.05). Compared to I_1, I_2 and I_3 increased SPAD values by 19.1% and 15.8%, respectively, indicating enhanced chlorophyll retention under better moisture availability. Among silicon treatments, Si, recorded a 19.3% increase in SPAD index over Si_1, while Si_3 (19.1%) and Si_5 (13.1%) also showed significant improvements, confirming the beneficial role of silicon in chlorophyll preservation (Table 2).

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. By the absence of irrigation, elevated concentrations of peroxidase and chlorophillase enzymes and reactive oxygen species (increase in O_2 and H_2O_2), which cause lipid peroxidation and a subsequent decrease in chlorophyll content (Choudhury *et al.,* 2022). Drought stress causes chlorophyll degradation, leading to reduced chlorophyll concentrations and disrupting photosynthetic pigments, which impairs gas exchange and stunts plant growth and production (Khayatnezhad and Gholamin, 2021). Silicon application enhances plant structure and photo-synthesis by increasing chlorophyll levels, likely due to silicon accumulating in epidermal cells, which protects the photosynthetic apparatus from damage. (Bhardwaj and Kapoor, 2021). Similar findings of lower chlorophyll content when irrigation was stopped were also reported by Muhammad *et al.,* (2022).

Proline content decreased with improved irrigation and silicon application (p<0.05). Compared to I_1, proline content declined by 7.2% under I_2 and by 3.9% under I_3, reflecting reduced stress conditions. Among silicon treatments, Si2 lowered proline content by 6.5% compared to Si_1, followed by Si_3 (5.5%) and Si_4 (3.2%), suggesting silicon's effectiveness in mitigating drought-induced stress responses (Table 2).

Proline, a heterocyclic amino acid that accumulates in the cytoplasm, aids in osmotic adjustment during stress and acts as an osmolyte, electron sink, radical scavenger and

Table 2: Effect of irrigation levels and silicon on yield attributes, biochemical parameters and relative water content (RWC) of barley.

Treatments	Weight of grains spike^{-1} (g)	Biological yield (q ha^{-1})	SPAD index	Proline content (µmol/g fresh wt)	Relative water content (%)
Main plot: Irrigation levels (I)					
I_1	1.25±0.18^{b}	58.91±12.67^{c}	37.15±4.16^{b}	9.37±0.22^{a}	50.51±5.03^{b}
I_2	1.81±0.34^{a}	82.19±5.12^{b}	44.27±2.34^{a}	8.70±0.43^{b}	60.18±3.35^{a}
I_3	1.88±0.21^{a}	89.95±8.73^{a}	43.00±4.58^{a}	8.78±0.41^{b}	58.75±3.02^{a}
SE(m)±	0.03	0.77	0.39	0.05	0.48
CD at 5%	0.10	3.12	1.58	0.19	1.95
Sub plot: Foliar silicon (Si)					
Si_1	1.38±0.28^{d}	65.34±16.60^{d}	38.29±5.57^{b}	9.31±0.29^{a}	52.19±6.50^{c}
Si_2	1.75±0.34^{b}	82.23±9.57^{b}	44.32±2.87^{a}	8.70±0.46^{d}	60.26±4.17^{a}
Si_3	1.89±0.30^{a}	87.86±12.60^{a}	44.15±4.42^{a}	8.72±0.62^{cd}	59.17±3.71^{a}
Si_4	1.66±0.43^{bc}	75.78±15.09^{c}	38.79±4.35^{b}	8.99±0.37^{bc}	55.22±6.17^{b}
Si_5	1.57±0.37^{c}	73.85±18.87^{c}	41.81±4.00^{a}	9.03±0.32^{b}	55.56±4.81^{b}
SEm±	0.04	1.21	0.83	0.10	0.79
CD at 5%	0.12	3.55	2.43	0.28	2.32
Interaction (I × Si)					
I at Si					
SE(m)±	0.12	2.03	1.34	0.16	1.32
CD at 5%	NS	6.27	NS	NS	NS
Si at I					
SE(m)±	0.07	1.73	0.88	0.11	1.08
CD at 5%	NS	6.48	NS	NS	NS

macromolecule stabilizer. Fewer studies have examined high proline levels as indicators of damage rather than stress tolerance (Hosseinifard *et al.,* 2022). Proline accumulates in plants under water stress, helping to stabilize proteins, cellular structures and maintain turgor. With sufficient irrigation, proline levels are lower due to reduced water stress and better overall plant health. (Ghosh *et al.,* 2022). The proline levels in stressed plants that decrease when silicon is added might be a sign that stress-related damage is decreasing. It turned out that silicon application in rice (Bhardwaj *et al.,* 2023) and sunflower (Ahmed and Tameemi, 2025) decreased the content of proline under stress.

Plant-water relations

Relative water content (RWC) responded significantly to irrigation and foliar silicon application (p<0.05). Compared to I_1, RWC increased by 19.2% under I_2 and 14.5% under I_3. Among silicon treatments, Si_2 showed the highest RWC, recording a 19.4% increase over Si_1. Si_3 (59.17%) and Si_4 (55.22%) were found to be statistically at par (p<0.05) (Table 2).

Relative water content has been demonstrated to be a valuable screening method for drought resistance in cereals and a trustworthy indicator of plant water status relative to their fully turgid condition. 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 (Yadav *et al.,* 2020). It is these effects that cause turgor loss in leaves. In contrast, irrigation maintains a strong turgor pressure and a relative leaf water content (Hemati *et al.,* 2022). The ability of silicon to maintain the relative water contents under water stress is a significant property (Bukhari *et al.,* 2021). The plant body's relative water content and nutrient absorption were reduced by water stress; however, Si treatment performed an excellent role of maintaining the turgor presser, which encouraged greater plant growth and productivity (Qamar *et al.,* 2020).

CONSLUSION

In conclusion, the growth, phenology, yield attributes and biochemical parameters of barley (*Hordeum vulgare* L.) are considerably influenced by the synergistic impact of irrigation levels and silicon application. The combination of silicon supplementation and optimal irrigation increases stress resistance, boosts nutrient absorption and maximizes water use efficiency. In addition to encouraging strong plant growth, this integrated strategy raises the potential production and enhances the quality of barley grains. The results highlight the importance of silicon application and strategic irrigation management for sustainable barley cultivation, especially in areas with limited water resources and unstable weather patterns. Future studies should aim to optimize agronomic practices for improved crop performance by researching further into the underlying processes of these interactions.

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Conflict of interest

All authors declare that they have no conflict of interest.

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