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Foliar Application of Potassium Silicate Mitigates Terminal Heat Stress in Wheat through Enhanced Antioxidant Defense and Physiological Stability

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Abstract:

Terminal heat stress during the reproductive phase severely impairs wheat (*Triticum aestivum* L.) productivity by inducing oxidative damage and disrupting physiological homeostasis. This study evaluated the role of foliar-applied potassium silicate in enhancing antioxidant defense and physiological resilience of wheat under varying sowing dates. A field experiment was conducted using a split plot block design with four sowing dates (25 October, 5 November, 15 November, and 25 November) and eight foliar treatments, including potassium silicate (2% and 3%) applied at booting and/or anthesis, potassium nitrate (2%), and an untreated control. Delayed sowing significantly intensified oxidative stress, as indicated by increased DPPH radical scavenging activity, superoxide dismutase (SOD), and catalase (CAT) activities, along with elevated lipid peroxidation and proline accumulation, while chlorophyll content declined. The application of 3% potassium silicate at both booting and anthesis markedly enhanced antioxidant capacity, recording the highest DPPH activity (22.70 units mg^{1} FW), SOD (457.6 mg^{1} FW), and CAT activity (695.43 HO min^{1} g^{1} FW), and significantly reduced lipid peroxidation (0.727 nmol cm^{1} FW) compared with the control. Additionally, this treatment improved chlorophyll content (3.194 mg g^{1} FW) and proline accumulation (0.612 mg g^{1} FW), indicating enhanced membrane stability and osmotic adjustment. These findings demonstrate that silicon-mediated modulation of antioxidant and osmoprotective mechanisms effectively mitigates terminal heat-induced oxidative stress in wheat, highlighting foliar potassium silicate as a promising strategy for enhancing crop resilience under warming climatic conditions.

Keywords: Antioxidant enzymes, Chlorophyll, Heat stress, Lipid peroxidation, Potassium silicate, Proline, Silicon, *Triticum aestivum* L

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated and strategically important cereal crops globally, serving a major share of daily caloric, fibre, protein and essential micronutrient intake for billions of people owing to its wider adaptability across diverse agro-ecological regions, higher productivity and usefulness in various food processing and consumption (OECD and FAO, 2020; Zheng *et al.,* 2025; FAO, 2024). It plays a central role in ensuring food and nutritional security, particularly in densely populated regions such as the Indo-Gangetic Plains, where wheat-based cropping systems dominate agricultural production (Jha *et al.,* 2023; Khedwal *et al.,* 2023; Farnworth *et al.,* 2023). The crop's wide adaptability, ease of storage, and versatility in food products have made it indispensable to both developed

and developing economies. Despite its global significance, wheat production is increasingly challenged by climate change, with rising temperatures posing a serious threat to its productivity and stability (IPCC, 2021). Heat stress, defined as temperatures exceeding the critical threshold required for normal growth and development, has become a major factor behind yield penalty, which restrict the varieties/ genotypes from expressing their potential in wheat-growing regions (Mohan *et al.,* 2023; Farhad *et al.,* 2023). This is particularly critical in tropical and subtropical areas, where terminal heat stress commonly coincides with the reproductive and grain filling phase due to late sowing or sudden temperature spikes (Bashir *et al.,* 2024; Zheng *et al.,* 2025).

Although silicon is not considered an essential nutrient for most plants but is widely known for its role in enhancing tolerance to abiotic stresses such as heat, drought, salinity, and heavy metal toxicity (Asgher *et al., 2024 and* Abdelaal *et al.,* 2020). Foliar application of potassium silicate (K_2SiO_3) and potassium nitrate (KNO_3) is an effective strategy for mitigating abiotic stress in crops through complementary physiological and biochemical mechanisms. Potassium silicate enhances stress tolerance by improving antioxidant defense, osmolyte accumulation, and nutrient homeostasis, thereby reducing reactive oxygen species (ROS), lipid peroxidation, and cellular damage while maintaining chlorophyll content and photosynthetic efficiency (Singh *et al.,* 2022; Aouz et al, 2023; Mohammadi et al, 2024 and Saleh and Soliemanzadeh, 2026). Silicon deposition also strengthens cell walls, regulates ion balance (K^+/Na^+), and improves water status and membrane stability under stress conditions (Alharbi et al, 2024). Field and experimental studies further confirm that foliar potassium silicate significantly enhances wheat growth and productivity under heat stress (Kaur et al, 2025). In contrast, potassium nitrate primarily supports stress mitigation by supplying essential potassium and nitrogen, which regulate stomatal conductance, osmotic balance, enzyme activation, and photosynthetic metabolism. Although both inputs are beneficial, potassium silicate generally provides superior protection due to its integrated structural and antioxidant regulatory roles in plant stress tolerance.

Overall, addressing heat stress in wheat requires an integrated approach combining physiological, genetic, and agronomic strategies. Enhancing the resilience of wheat to high temperatures is crucial for sustaining productivity and ensuring global food security in the face of ongoing climate change.

2. Materials and Methods

Experimental Site: The present study was conducted at Punjab Agricultural University, Ludhiana, during the Rabi seasons of 2021–22 and 2022–23. Meteorological data recorded at the agro-observatory indicated that during the Rabi season of 2021–22, the mean daily maximum temperature ranged from 13.6°C to 39.94°C, while the minimum temperature ranged from 4.9°C to 21.4°C. In 2022–23, the minimum and maximum temperatures varied from 3.5°C to 39.0°C. Notably, during the reproductive stage, elevated minimum temperatures were more detrimental than higher maximum temperatures. The maximum temperature exceeded 30°C during the 12th and 10th standard meteorological weeks in 2021–22 and 2022–23, respectively (Fig 1&2). An abrupt rise in minimum temperature above normal from the 1st to 5th standard week accelerated crop phenology, leading to earlier onset of the reproductive phase, with temperatures surpassing 12°C from the 8th week in both years (Fig 1&2). Increased cloudiness during the booting and heading stages elevated minimum temperatures and shortened the duration of the booting phase.

Experimentation, factors and their levels: A split plot design was used with three replicates during both the years. The main plot was used to investigate the sowing dates whereas the foliar spray treatments were laid out in the subplots. The foliar sprays were given at anthesis stage and booting stage at doses and frequency mentioned in Table 1. In treatment 2 to 5, only one foliar application of potassium silicate, either at anthesis or booting stage, whereas in treatment 6 &7 two foliar sprays of potassium silicate i.e; at anthesis and booting stage were given. Similarly for potassium nitrate two foliar application, at anthesis and booting stage, were given. All the crop husbandry operations were performed as per the Punjab Agricultural University recommendations for wheat cultivation (Anonymous, 2025).

2.1. Sampling and Biochemical Analyses

All the biochemical parameters viz; Superoxide dismutase, Catalase, DPPH radial scavenging activity, lipid peroxidation, proline content, chlorophyll content were

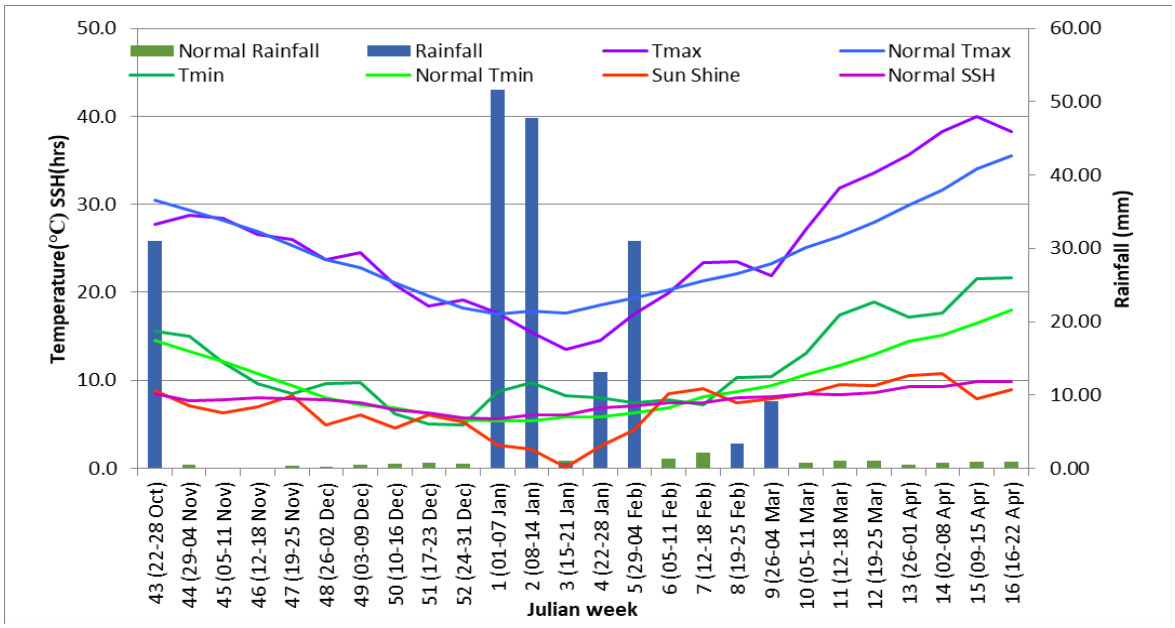

Fig. 1: Meteorological week wise maximum & minimum temperature (°C), sunshine hours (hrs) and rainfall (mm) during 2021-22 at Ludhiana

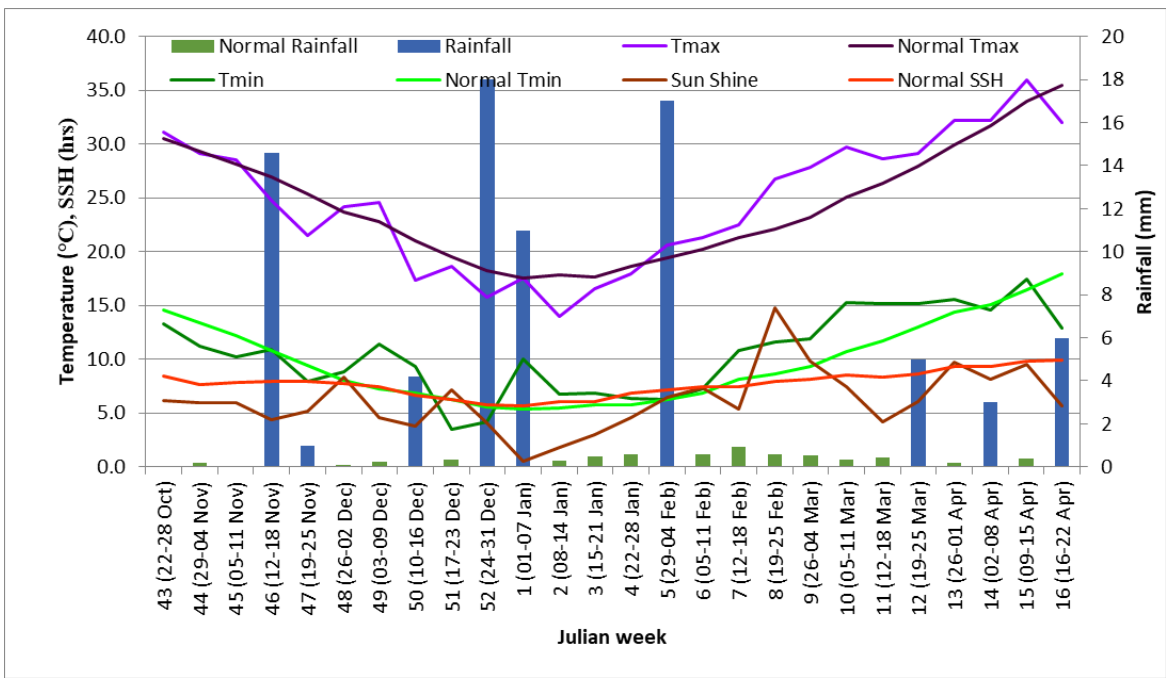

Fig. 2: Meteorological week wise maximum & minimum temperature (°C), sunshine hours (hrs) and rainfall (mm) during 2022-23 at Ludhiana

analysed10 days after anthesis. Flag leaves were collected from all the treatments and analysed by using different protocols for different enzymatic and non-enzymatic activities.

2.2. Superoxide Dismutase (SOD)

The SOD activity was determined by nitro blue tetrazolium (NBT) photoreduction method using procedure of Beauchamp and Fridovich (1971).

2.3. Catalase (CAT)

The catalase activity was measured using protocol of Aebi (1983). The decline in absorbance of resulting solution was recorded at 240 nm for 2 minutes (at an interval of 30 seconds) and the absorbance was taken at 240 nm.

2.4. DPPH Radical Scavenging Activity

The radical scavenging activity of test samples against 2, 2-diphenyl-1- picrylhydrazyl (DPPH) was measured using

Table 1. Effect of date of sowing and foliar treatments on the physiological apparatus of wheat plant

Treatment	SOD activity (mg^{-1} FW)	CAT activity (H_2O_2 min^{-1} g^{-1} FW)	DPPH activity (unit mg^{-1} FW)	Lipid peroxidation (nmol cm^{-1} FW)	Proline (mg g^{-1} FW)	Chlorophyll (mg g^{-1} FW)
Date of sowing						
Oct-25	307.5	416.35	17.30	1.028	0.177	2.546
Nov-05	360.5	598.15	18.50	1.209	0.460	2.786
Nov-15	397.2	665.85	19.10	1.469	0.535	2.628
Nov-25	428.9	739.00	19.94	1.623	0.635	2.564
LSD (p=0.05)	16.94	38.79	1.07	0.093	0.021	0.010
Foliar spray						
T1: Control	259.50	323.92	14.78	2.831	0.272	1.988
T2: Pot. silicate @ 2 % at booting	336.45	615.98	16.59	1.502	0.381	2.495
T3: Pot. silicate @ 3 % at booting	336.8	617.22	16.69	1.419	0.392	2.529
T4: Pot. silicate @ 2 % at anthesis	393.6	630.19	16.59	1.275	0.461	2.548
T5: Pot. silicate @ 3 % at anthesis	411.2	632.21	20.40	1.092	0.515	2.682
T6: Pot. silicate @ 2 % at booting +anthesis	423.6	658.46	22.10	0.893	0.564	2.891
T7: Pot. silicate @ 3 % at booting + anthesis	457.6	695.43	22.70	0.727	0.612	3.194
T8: Pot. Nitrate@ 2 % at booting + anthesis	369.5	665.29	21.23	0.904	0.415	2.723
LSD (p=0.05)	101.09	225.84	1.52	0.131	0.020	0.303
Interaction	95.89	150.85	2.05	0.085	0.015	0.025

the method of Beta *et al.* (2005). The absorbance of the reaction mixture was recorded at 520 nm, and scavenging activity was calculated as:

The percent scavenging activity was calculated by formula:

% scavenging activity =1- {(Absorbance of sample / Absorbance of control)} ×100

2.5. Lipid Peroxidation

The peroxidation of membrane lipids was calculated in terms of malondialdehyde content (Okhawa *et al.,* 1979). The absorbance was recorded at 532 nm and 600 nm. The amount of malonaldehyde produced was calculated using molar extinction coefficient of 155 mM^{-1} cm^{-1}.

MDA equivalents (nmol ml^{-1}) = $[(A_{532} - A_{600})/ 155\ 000] \times 10^6$

2.6. Proline Content

Free proline was estimated using the acid-ninhydrin method of Bates *et al.* (1973) and expressed as mg g^{-1} FW. The absorbance of toluene phase was read at 520 nm and toluene was used as blank. The proline content was expressed in terms of mg g^{-1} FW using proline standards (10-50 µg/ml).

2.7. Chlorophyll Content

The chlorophyll content was estimated using procedure of Hiscox and Israelstam (1979) and is expressed as mg g^{-1} FW. The absorbance of the extract obtained after the procedure was taken at 645 nm and 663 nm.

$$\text{Total Chlorophyll} = \frac{V}{[20.2\ A_{645} + 8.02\ A_{663}] \times W \times 1000}$$

Where

A_{645} and A_{663} were absorbances at 645 and 663 nm, V was total volume (ml) of extract, FW was fresh weight (g) of tissue.

3. Results

3.1. Effect of Date of Sowing

3.1.1. Enzymatic Activity

Date of sowing significantly influenced antioxidant parameters (LSD p=0.05). DPPH activity increased progressively from 17.30 (25 Oct) to 19.94 mg^{1} FW (25 Nov) (Table 1), indicating enhanced free radical scavenging under delayed sowing. Similarly, SOD activity increased from 307.5 to 428.9 mg^{1} FW, while CAT activity rose from 416.35 to 739.00 HO min^{1} g^{1} FW. This suggests that late sowing exposed plants intensified oxidative stress dueto terminal heat stress, triggering enhanced ROS generation and subsequent activation of enzymatic antioxidant systems.

Enhanced SOD and CAT activity under heat stress is a protective adaptation to detoxify superoxide radicals and hydrogen peroxide (Hasanuzzaman *et al.,* 2022; Farooq *et al.,* 2022; Awasthi *et al.,* 2023).

3.1.2. Non-enzymatic Activity

Lipid peroxidation increased significantly from 1.028 to 1.623 nmol cm^{1} FW with delayed sowing indicating membrane damage due to oxidative stress. Similarly, proline content increased from 0.177 to 0.635 mg g^{-1} FW, confirming osmotic adjustment and stress mitigation response.The data clearly reveals that there was significant effect of sowing date on proline content. The accumulation of proline increases progressively with delay in sowing of wheat crop with prolongation of heat stress during anthesis stage. The proline content increase by 72.1 % under November 25 as compared to October 25. Increased proline accumulation under terminal heat has been widely reported as a stress indicator and protective osmolyte (Sattar *et al.,* 2020; Sharma *et al.,* 2022; Raza *et al.,* 2023).

Maximum chlorophyll (2.786 mg g^{1} FW) was observed under 5 Nov sowing, while late sowing reduced chlorophyll (2.564 mg g^{1} FW), likely due to accelerated chlorophyll degradation and thylakoid damage. These findings align with climate-resilient wheat management studies (Jat *et al.,* 2023).

3.2. Effect of Foliar Treatments

3.2.1. Enzymatic Activity

Foliar application of potassium silicate significantly enhanced antioxidant defense. The 3% potassium silicate applied at booting + anthesis recorded the highest SOD (457.6 mg^{1} FW), and CAT (695.43 H_2O_2 min^{-1} g^{-1} FW) activities. These improvements highlight the role of silicon in enhancing enzymatic detoxification of ROS (Luyckx *et al.,* 2023).

3.2.2. Non-enzymatic Activity

Lipid peroxidation was highest in the control (2.831 nmol cm^{-1} FW) and lowest under 3% potassium silicate at booting + anthesis (0.727 nmol cm^{-1} FW), demonstrating silicon's effectiveness in stabilizing cellular membranes (Zargar *et al.,* 2023). DPPH scavenging activity, proline and chlorophyll contents were significantly enhanced by silicon application, with maximum values of 22.70 unit mg^{-1} FW, 0.612 mg g^{-1} FW and 3.194 mg g^{-1} FW, respectively. These results indicate improved osmotic balance and photosynthetic efficiency (Aouz *et al.,* 2023).

Although potassium nitrate improved physiological traits compared to the control, it was less effective than potassium silicate, emphasizing the unique protective role of silicon.

3.2.3. Interaction Effect (Date × Foliar Treatment)

The interaction between sowing date and foliar treatment was significant for all parameters, indicating that the beneficial effects of potassium silicate were more pronounced under delayed sowing conditions. Silicon application effectively mitigated oxidative stress, particularly when heat stress intensity was high.

Analysis of variance (ANOVA) revealed that the main effects of sowing date and foliar spray treatments, as well as their interaction, were significant ($p \leq 0.05$) for all physiological parameters studied. Delayed sowing significantly increased antioxidant enzyme activities, lipid peroxidation, and proline accumulation, while reducing chlorophyll content. Foliar application of potassium silicate, particularly at 3% applied at both booting and anthesis, significantly enhanced DPPH scavenging activity, SOD and CAT activities, and chlorophyll content, while markedly reducing lipid peroxidation. The significant Date × Foliar interaction indicates that silicon

application was effective in mitigating oxidative stress under late sowing conditions.

4. Conclusion

Delayed sowing intensified oxidative stress in wheat, as evidenced by increased enzymatic and non-enzymatic antioxidant activity, along with reduced chlorophyll content. Foliar application of 3% potassium silicate at booting and anthesis effectively mitigated these adverse effects by enhancing antioxidant defense and maintaining physiological stability. Silicon-based foliar nutrition thus represents a promising climate-smart strategy for improving wheat resilience to terminal heat stress.

Declarations

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Conflict of interest

The authors declare that they have no conflict of interest.

Author's contribution

Maninder Kaur: Data collection, compilation and analysis, interpretation of results, manuscript drafting; J S Deol: Planning and manuscript editing; Neha Gupta: Biochemical analysis and interpretation. All the authors read and finalized the manuscript.

Ethical Approval

This article doesn't contain any study involving ethical approval.

Declaration on the use of Generative AI or AI-assisted technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript. All text, data interpretation, and analysis were conducted entirely by the authors.

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