OPEN ACCESS Pakistan Journal of Weed Science Research

Research Article

Genotype-Specific Influence of Exogenous Silicon on Wheat Under NaCl-induced Salinity: A Pot Experiment

Abdullah[1]*, Sartaj Aziz[2], Muhammad Amir Zia[1], Ihsan Ullah Khan[3], Ashtar Khan[4], Husnal Maab[5], Shah Zaib[6], Tanweer Kumar[7] and Nur-ul-Haq[7]

[1]National Institute for Genomics and Advanced Biotechnology, National Agricultural Research Centre, Islamabad, Pakistan; [2]Department of Life Science, Guizhou University, China; [3]Oilseeds Program, Crop Sciences Institute, National Agricultural Research Centre, Islamabad, Pakistan; [4]Plant Genetic Resources Program, National Agricultural Research Centre, Islamabad, Pakistan; [5]Department of Botany Abdul Wali Khan University Mardan, Pakistan; [6]CAS Key Laboratory of Environmental and Applied Microbiology, Environmental Microbiology, Key Laboratory of Sichuan Province, Chengdu Institute of Biology, Chinese Academy of Sciences, China; [7]Sugar Crops Research Institute, Charsadda Road 23210 Mardan, Agriculture Fisheries and Co-operative Department Khyber Pakhtunkhwa, Pakistan.

Abstract | The objective of this study was to evaluate how exogenously applied silicon improves the agronomic performance of three wheat varieties namely (Bakhtawar, Akbar, and Pirsabaq) under different salinity levels, considering its role in enhancing crop vigor and competitiveness in saline agricultural environments. A controlled pot experiment was conducted using a Completely Randomized Design (CRD) in National Agriculture Research Center (NARC) Islamabad from 2024 to 2025, with a 2-factor factorial arrangement (silicon × salinity) and three replicates per treatment. The treatments included a control, silicon application (15 mM), two NaCl-induced salinity levels (50 mM and 100 mM), and their respective silicon–salinity combinations. Key agronomic attributes, including plant height, stem diameter, leaf area, tiller number, spike characteristics, and flag leaf development were studied after 45 and 60 days of treatment. Salinity markedly reduced plant growth across the wheat varieties, while silicon application produced measurable improvements—for example, plant height increased by 4–11%, stem diameter improved by 2–4%, leaf number increased by up to 20%, and leaf length increased by 4–17% under Si-salinity treatments compared with salinity alone. While silicon application conferred some partial alleviation of salt-induced stress, manifesting as slight enhancements in specific traits such as plant height, leaf area, and spikelet number, these ameliorative effects were inconsistent and highly genotype-dependent. These findings indicate that silicon partially alleviates salinity-induced stress in wheat, with effects varying among varieties and salinity levels, highlighting its variety-specific benefits under moderate salinity conditions and the need for further research on optimal application strategies.

Received | October 19, 2025; **Accepted** | December 01, 2025; **Published** | December 13, 2025
***Correspondence** | Abdullah, National Institute for Genomics and Advanced Biotechnology, National Agricultural Research Centre, Islamabad, Pakistan; **Email:** abdu84885@gmail.com
Citation | Abdullah, S. Aziz, M.A. Zia, I.U. Khan, A. Khan, H. Maab, S. Zaib, T. Kumar and Haq NU. 2025. Genotype-specific influence of exogenous silicon on wheat under NaCL-induced salinity: A pot experiment. *Pakistan Journal of Weed Science Research,* 31(4): 217-227.
DOI | https://dx.doi.org/10.17582/journal.pjwsr/2025/31.4.217.227
Keywords | Wheat, Salinity stress, Silicon application, Genotype response, Salt tolerances

Introduction

Soil salinity is a global threat to agriculture because it affects crop yields and growth in salt-affected areas (Batlle-Sales, 2023). Salt stress hampers crop growth and yield in a various ways (Shahid *et al*., 2020). Salt stress affects crop plants in two ways: osmotic stress and ion toxicity (Hasanuzzaman and Fujita, 2022). Salinity stress exhibited secondary impacts on assimilate generation, cell growth and membrane function, and cytosolic metabolism (Ludwiczak *et al*., 2021). Salinity stress can regulate the activity of two ethylene biosynthesis enzymes, 1-amino-cyclopropane-1-carboxylic acid (ACC) synthase and ACC oxidase (Houben *et al*., 2024). Various growth stages of wheat are simultaneously affected by salinity. This results in stunted growth and lower biomass production due to the shifting of plant metabolism towards stress management and adjustment of osmotic irregularities (Ghadirnezhad *et al*., 2023). Under high salinity, increased sodium (Na^+) and chloride (Cl^-) concentrations lead to an ionic imbalance in plant tissues, resulting in reduced nutrient uptake (Arif *et al*., 2020). Furthermore, a decrease in the uptake of potassium (K^+) and calcium (Ca^{++}), inactivation of various enzymes, inhibition of protein synthesis, slow rate of photosynthesis, leaf and stem senescence, and early leaf senescence are all noticeable symptoms of salt stress (Imtiaz *et al*., 2023). While the impacts of salinity are well documented, strategies to mitigate these effects particularly using silicon supplementation remain underexplored in wheat, highlighting the need to evaluate variety-specific responses and optimal application methods under saline conditions. In Pakistan, salinity has caused a 25% reduction in crop yield (Syed *et al*., 2021). In 2017, waterlogging and salinity in Pakistan caused severe losses in crop yield, reaching Rs. 880 million ($28.5 million), while the estimation of total annual economic damage was 300 USD million (Syed *et al*., 2021). It is estimated that the land losses due to salinity are 28000 to 40000 ha of land and because of low crop yield due to high salinity there is a loss of about US$ 230 million per year (Murtaza *et al*., 2023). Wheat faces various biotic and abiotic stresses that severely compromise its productivity. The global wheat production volume in the year 2020-21 was over 768.9 million metric tonnes (Dhakal *et al*., 2021). Wheat production in Nepal reached 2,210 thousand tonnes in 2020, representing a 5.73% increase compared to the previous year (Subedi and Khadka, 2022). Although wheat accounts for the largest harvested area (38.8%) among cereals such as rice and maize in Nepal, its overall productivity remains the lowest (Katel *et al*., 2023). Salinity has adverse effects on agriculture and the economy of Pakistan. To overcome this issue, silicon fertilizers are applied to plants with salt stress (Attiq *et al*., 2021). Wheat is a good source of trace minerals, such as selenium and magnesium, which are essential for good health. Silicon is a chemical element with the symbol Si and atomic number 14 (Islam *et al*., 2024). It is a tetravalent metalloid, meaning it has properties of both metals and nonmetals, and is the second most abundant element in the Earth's crust. Silicon (Si) is naturally present in plant tissues and contributes to stress tolerance by enhancing ion balance, antioxidative defense, and water-use efficiency (Sirhindi *et al*., 2025). However, its effectiveness varies among genotypes and salinity levels, with some studies reporting benefits only under moderate salinity or in specific wheat varieties. The quantity of Si accessible to plants has decreased owing to repeated cropping and the use of artificial fertilizers (Barão, 2023). In soils, silicon (Si) mainly occurs as silicates and oxides, with free Si present only in low concentrations, typically ranging from 0.1 to 0.6 mM (Tubaña and Heckman, 2015). The plants uptake Si as silicic acid [Si(OH)4] and found in crystalline form as silica gels (SiO–nH2O) in the shoots and leaves (Pontigo *et al*., 2015). The effectiveness of Si in reducing negative impacts of salt stress and enhancing salt tolerance in plants has been widely studied, but the underlined mechanism is marginally understood (Dabravolski and Isayenkov, 2024). The enhanced salinity tolerance with Si supplementation is mostly by decreasing the plant Susceptibility to osmotic and ionic stresses (Rizwan *et al*., 2015). Decreasing the Na^+ uptake and maintaining the optimum Na^+/K^+ ratio. Silicon-mediated tolerance in plants alters the transcriptional patterns of genes related to aquaporins, phytohormone biosynthesis, polyamine biosynthesis, salinity stress, and ion transporters (Farooq *et al*., 2024).

This study hypothesized that silicon supplementation would partially alleviate NaCl-induced salinity stress in bread wheat and that the magnitude of response would differ among varieties. To test this, we evaluated the effects of Si on growth and yield traits in three wheat varieties (Bakhtawar, Akbar-2019, and Pirsabaq) under varying NaCl concentrations.

Materials and Methods

Experiment design and site

The experiment followed a 3 × 3 × 2 factorial Completely Randomized Design (CRD), with three wheat varieties (Bakhtawar, Akbar-2019, Pirsabaq), three NaCl concentrations (0, 50, and 100 mM), and two silicon treatments (0 and 15 mM). Each treatment combination was replicated three times. Pots were maintained under natural light at NARC, Islamabad (33.6°N, 73.0°E), with mean temperature 20–26°C and relative humidity 55–65%. Watering was performed with deionized water to maintain field capacity.

Plant materials and growth conditions

Seeds were obtained from certified local suppliers under the Wheat Program of NARC to ensure varietal purity. The soil used was loamy (sand 42%, silt 35%, clay 23%), with pH 7.6 and EC 2.1 dS m^{-1}, and baseline available Si 18 mg kg^{-1}. No fertilizers were added to avoid confounding nutrient effects. Pots were irrigated every two days with deionized water to maintain moisture near field capacity.

Treatment preparation and application

All solutions were freshly prepared before each application to maintain chemical stability and bioavailability.

Silicon solution

Sodium silicate (Na_2SiO_3) was used as the silicon source. To prepare 1 L of 15 mM Si solution:

$$\text{Mass off } (Na_2SiO_3)\ (g) = \text{Molarity } (M) \times \text{Molar Mass } (g/mol) \times \text{Volume } (L)$$

Calculated mass= 2 g Na_2SiO_3. The solid was dissolved in 1 L of distilled water, mixed thoroughly, and stored in labeled bottles for further use.

Sodium chloride solutions

Two distinct concentrations of sodium chloride (NaCl) were prepared to induce salt stress (Ashraf and Saeed, 2006):

- 50 mM NaCl solution: Prepared by dissolving 3 g of NaCl in 1 liter of distilled water.
- 100 mM NaCl solution: Prepared by dissolving 6 g of NaCl in 1 liter of distilled water. Treatment application

Treatments were initiated 40 days after sowing. The experimental treatments applied to each variety were as follows:

Treatments	Solutions	Varieties
T1	Control	Pirsabaq
T2	Silicon 15 mM	Pirsabaq
T3	Salt 50 mM	Pirsabaq
T4	Silicon + Salt 50 mM	Pirsabaq
T5	Salt 100 mM	Pirsabaq
T6	Silicon + Salt 100 mM	Pirsabaq
T7	Control	Bakhtawar
T8	Silicon 15 mM	Bakhtawar
T9	Salt 50 mM	Bakhtawar
T10	Silicon + Salt 50 mM	Bakhtawar
T11	Salt 100 mM	Bakhtawar
T12	Silicon + Salt 100 mM	Bakhtawar
T13	Control	Akbar
T14	Silicon 15 mM	Akbar
T15	Salt 50 mM	Akbar
T16	Silicon + Salt 50 mM	Akbar
T17	Salt 100	Akbar
T18	Silicon + Salt 100 mM	Akbar

Data collection and agronomic parameter assessment

The key agronomic parameters systematically measured in this study to evaluate growth and yield performance included plant height, stem diameter, number of leaves, longest leaf length and width, tiller number, number of spikes, number of spikelets, spike length, flag leaf length, and flag leaf width. Measurements were taken at 45 and 60 days after treatment. Plant height and spike length were recorded from the base to the apex using a ruler. Leaf and flag-leaf areas were estimated as length × width × 0.75 (Watson, 1947). Fresh and dry weights were determined using five plants per pot; dry mass was obtained after oven-drying at 70 °C for 48 h.

Statistical analysis

Data were subjected to factorial ANOVA using SPSS v. 20 to test the main and interaction effects of variety, salinity, and silicon. Means were separated by Duncan's Multiple Range Test (DMRT) at $p < 0.05$. Homogeneity of variance was checked prior to analysis data.

Results

Effect of silicon and salt on plant height, diameter and number of leaves

In the current study, plant height was significantly influenced by both salinity and silicon (Si) treatments across all wheat varieties. For the Pirsabaq variety, salinity stress alone (T3 and T5) caused a notable reduction in plant height by 9.4% and 2.7%, respectively, compared to the control (T1). The application of Si alone (T2) resulted in a slight reduction (6.9%), while co-application of Si with salinity (T4 and T6) moderately improved plant height by 4.1% and 2.8%, respectively, suggesting a partial mitigation of salt-induced growth inhibition by silicon supplementation. In the Bakhtawar variety, all treatments except T6 showed a positive effect on plant height. The highest increase was observed under T4 (11.9%) and T3 (11.8%), followed by T2 (4.2%) and T5 (1.9%). Treatment with Si under high salt stress (T6) slightly improved plant height (3.7%) compared to T5, indicating that Si alleviated high salinity stress to some extent. In Akbar, Si treatment alone (T2) and under severe salt stress (T6) slightly decreased plant height (1.9% and 3.3%, respectively). However, under moderate salt stress (T3), plant height increased significantly (8.5%), and co-application of Si with 50 mM NaCl (T4) also led to a positive response (6.2%), suggesting that Akbar is more responsive to moderate salinity when aided by Si (Figure 1). Stem diameter showed variable responses among the three wheat varieties under salt and silicon treatments. In Pirsabaq, a minor increase was observed across most treatments. The highest increment was observed under T3 and T5 (3.39%), whereas Si alone (T2) and in combination with 50 mM salt (T4) slightly enhanced the diameter by 1.69% and 1.13%, respectively. A negligible reduction was noted under T2 (0.56%). In contrast, Bakhtawar showed a clear decline in stem diameter under all treatments except T4, which resulted in a small increase (1.4%). The reductions were more pronounced under T6 (13.7%) and T2 (9.3%), indicating a higher sensitivity of this variety to both salinity and silicon application. Akbar responded positively under T2 (11.8%) and moderately under T3 and T4 (2.01, 2.4%). However, stem diameter decreased slightly under T5 (1.5%) and more noticeably under T6 (7.3%). This suggests that moderate salt stress may promote stem diameter in Akbar, particularly when combined with silicon (Figure 2). The number of leaves varied in response to different treatments across the three wheat varieties. In Pirsabaq, silicon alone (T2) had no significant effect, while moderate salt stress (T3) reduced leaf number by 6.8%. However, T4 significantly increased leaf production by 20.4%, indicating a strong synergistic effect of Si and moderate salinity. In contrast, T5 and T6 resulted in reductions of 4.5% and 2.2%, respectively. Bakhtawar showed a slight increase under T2 (5%) and T4 (6.2%), with no change in T3. Treatments T5 and T6 led to similar reductions of 3.7%, suggesting moderate tolerance but limited benefit under high salinity, even with Si application. Akbar exhibited a decrease under T2 (2.4%), T3 (6.6%), and T4 (4.9%). Notably, co-application of Si under 100 mM salt (T6) improved leaf number by 7.4%, and T5 alone increased it by 9.9%, highlighting a unique positive response of this variety to high salt stress (Figure 3).

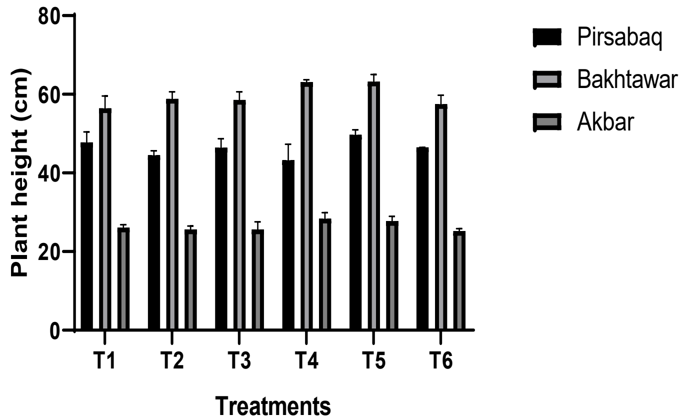

Figure 1: *Effect of silicon and salt on plant height of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments (p < 0.05) based on factorial ANOVA.*

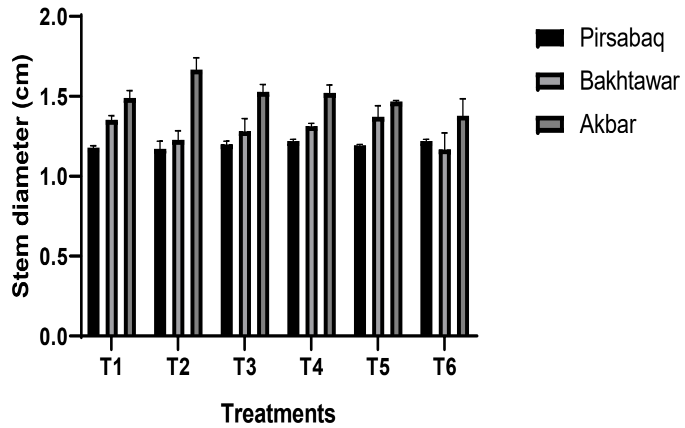

Figure 2: *Effect of silicon and salt on stem diameter of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments (p < 0.05) based on factorial ANOVA.*

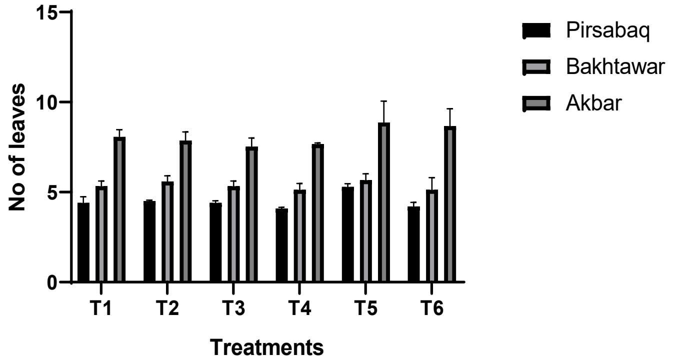

Figure 3: *Effect of silicon and salt on number of leaves of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

Effect of silicon and salt on leaf length and area

Leaf length exhibited contrasting responses to different treatments among the wheat varieties. In Pirsabaq, Si application alone (T2) and in combination with high salinity (T6) led to reductions of 6.7% and 7.6%, respectively. A substantial improvement was observed under T4, where leaf length increased by 16.8%. In contrast, T3 and T5 caused reductions of 4.3% and 9.3%, respectively, indicating moderate to severe sensitivity to salt stress alone. Bakhtawar showed a highly positive response to Si alone (T2), with an increase of 29.85% in leaf length. A smaller increase was noted under T4 (3.8%), while slight reductions were observed under T3 (2.7%) and T6 (15.8%) treatments. T5 did not contribute positively, suggesting that the beneficial effect of Si diminishes under high salt conditions. Akbar showed reduction in leaf length under T2 (10.2%) and T6 (7.3%). However, T3, T4, and T5 treatments improved leaf length by 3.6%, 4.6%, and 8.2%, respectively. This indicates that Akbar benefited more from the combined salt stress and Si treatment than from Si treatment alone (Figure 4). Leaf area varied considerably among the wheat varieties under different Si and salinity treatments. In Pirsabaq, a strong positive effect was observed under T4, where leaf area increased by 31.9%. A mild increase was recorded under T6 (6.3%), while reductions were noted under T2 (12.3%), T3 (2.05%), and T5 (7.5%). These results suggest that Pirsabaq is responsive to the combined application of Si and moderate salinity but is sensitive to Si alone or higher salinity levels without silicon. Bakhtawar showed its highest improvement under moderate salinity (T3), with a 32.3% increase in leaf area. T4 and T5 also led to moderate increases (7.21% and 3.2%, respectively). However, Si alone (T2) and high salt with Si (T6) caused reductions of 7.6% and 19.8%, respectively. This indicates that Bakhtawar performed best under moderate salt stress and may not benefit from silicon supplementation at higher salt concentrations. In Akbar, all treatments reduced the leaf area. The most severe decline was under T6 (30.5%), followed by T2 (19.7%) and T3 (6.1%). Minor decreases were observed under T4 (1.02%) and T5 (0.12%). This variety appears highly sensitive to both salinity and silicon, with no improvement even under moderate stress (Figure 5).

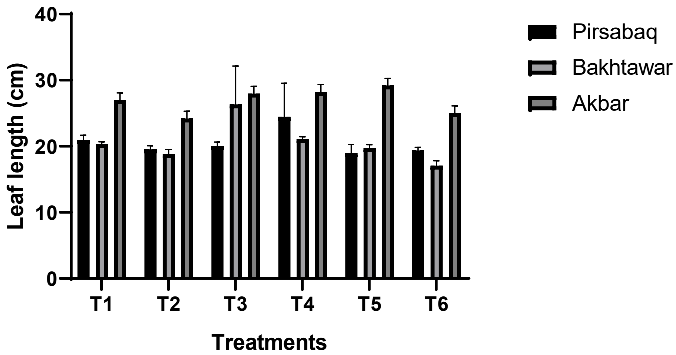

Figure 4: *Effect of silicon and salt on leaf length of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

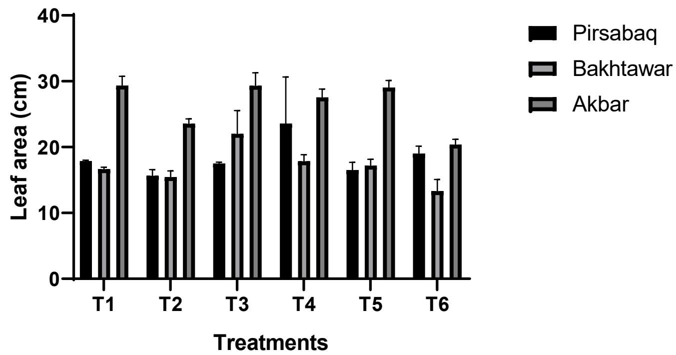

Figure 5: *Effect of silicon and salt on leaf area of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

Effect of silicon and salt on number of tillers, spikes and spikelets

The number of tillers per plant varied considerably among the three wheat varieties under different treatment conditions. In Pirsabaq, a marked reduction in tiller number was observed under T2 (25%), T4 (43.7%), and T6 (53.1%). However, T3 and T5 improved tiller number by 25% and 75%, respectively, suggesting that salt alone at certain levels might stimulate tiller development in this variety. In Bakhtawar, all treatments significantly enhanced the number of tillers compared to the control. Si alone (T2) resulted in a 1.0-time increase, whereas T3 increased the tiller number by 1.3 times. The combined application of Si and salt (T4) further elevated tillers by 2.0 times. The most substantial increases were seen under T5 and T6, with 3.6 and 4.0 times more tillers, respectively, indicating an exceptional tillering response to combined salinity and Si treatment in this variety. In contrast, Akbar exhibited a reduction in tiller number under T2, T3, and T4 by 26.6%, 16.6%, and 33.3%, respectively. Slight improvements were observed under T5 (20%) and T6 (6.6%), showing limited resilience to stress and the promotion of tiller formation by Si treatment (Figure 6). The number of spikes per plant varied across wheat varieties under different treatments. In Pirsabaq, Si application alone (T2) and in combination with 50 mM salt (T4) increased spike number by 7.1%, while T3 and T5 showed no change. A reduction of 7.1% was recorded under T6, suggesting that silicon may slightly improve spike production under moderate salt but not under severe stress. Bakhtawar exhibited a more variable response to the treatments. Treatments T2 and T6 caused reductions of 7.9% and 15.3%, respectively. A sharp decline was seen under T3 with 30.7% reduction. However, both T4 and T5 significantly enhanced spike numbers by 15.3%, indicating that spike production improved under salt or combined Si and salt stress under certain conditions. In Akbar, Si alone (T2) and its combination with 50 mM salt (T4) led to small increases in spike number by 6.5% and 3.5%, respectively. A considerable reduction was observed under T3 (18.9%) and T6 (14.2%). Treatment T5 had no significant effect. These findings suggest Akbar responds slightly better to Si under moderate stress but is sensitive to salt stress alone (Figure 7). The number of spikelets per plant showed both positive and negative trends across the three wheat varieties under various treatments. In Pirsabaq, application of Si alone (T2) improved the spikelet number by 6.5%, whereas T3 and T5 resulted in reductions of 18.9% and 14.2%, respectively. A modest increase was observed under T6 (11.8%), whereas T4 led to a slight reduction of 3.5%, suggesting moderate tolerance to combined salt and Si treatments. Bakhtawar displayed the strongest positive response, particularly under T3 and T4, where spikelet numbers increased by 70.2% and 83.2%, respectively. Si alone (T2) had no effect, while T5 and T6 enhanced spikelet number by 26.7% and 30.5%. This indicates that Bakhtawar is highly responsive to both salt stress and Si, especially in combination. In Akbar, the number of spikelets remained stable under T2, T3, and T4, with no change compared to the control group. However, slight increases were noted under T1 (7.5%) and T5 (6.1%), whereas T6 resulted in a small reduction of 5.1%. These results suggest that Akbar maintains consistent spikelet production under moderate stress, with limited benefits from Si (Figure 8).

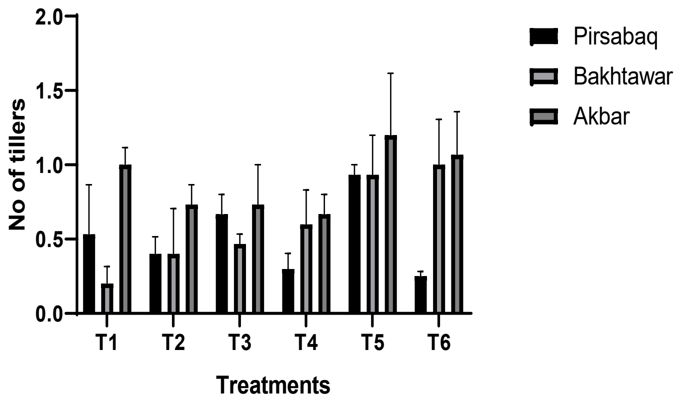

Figure 6: *Effect of silicon and salt on number of tillers of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

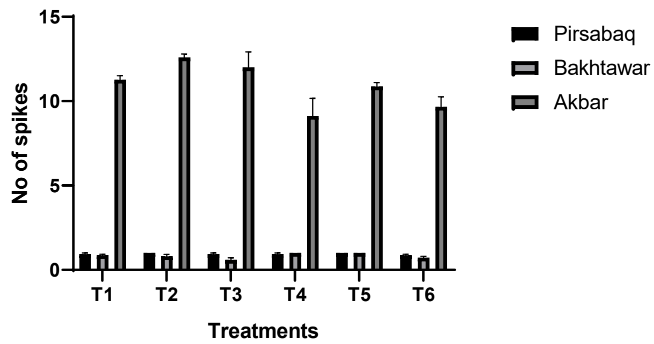

Figure 7: *Effect of silicon and salt on number of spikes of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

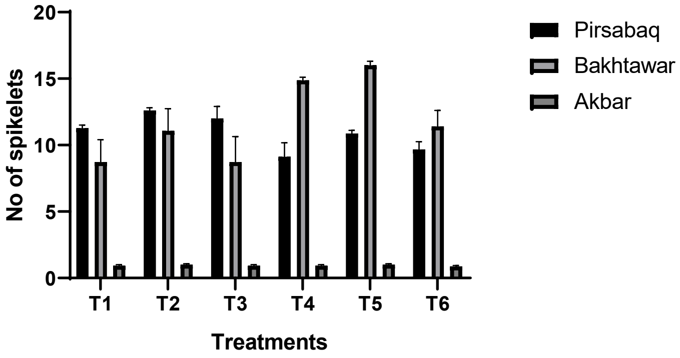

Figure 8: *Effect of silicon and salt on number of spikelets of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

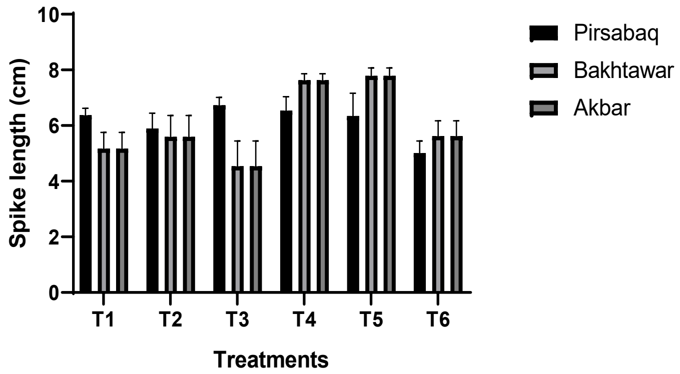

Figure 9: *Effect of silicon and salt on spikes length of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

Effect of silicon and salt on spike length, flag leaf area and number of grains

Spike length was influenced differently across the three wheat varieties in response to Si and salinity treatments. In Pirsabaq, a slight improvement was observed under T3 (2.7%) and T2 (5.7%), while T4 and T6 led to marginal reductions of 0.34% and 21.2%, respectively. The most notable decline occurred under T5, indicating that high salinity alone had a strong negative impact on spike elongation in this variety. In contrast, Bakhtawar showed considerable enhancement in spike length under combined salt and Si treatments. T4 and T5 improved spike length by 47.6% and 50.7%, respectively. A slight increase was also observed under T1 (8.2%). However, a notable reduction occurred with Si alone (T2:12.1%), indicating that Si alone did not promote spike elongation in this variety. Interestingly, Akbar showed an identical response pattern to Bakhtawar. Treatments T4 and T5 again led to significant increases in spike length (47.6% and 50.7%), while T2 resulted in a reduction of 12.1%. A mild increase under T1 (8.2%) and slight improvement under T3 (same as Bakhtawar) were also observed (Figure 9). Flag leaf area showed a range of responses under silicon and salt stress treatments across all three wheat varieties. In Pirsabaq, all treatments resulted in improvements compared to the control. The highest increase was recorded under T4 (19.1%), followed by T1 (17.8%) and T3 (14%). Smaller gains were observed under T2 (5.7%) and T6 (6.1%), suggesting that both moderate salinity and silicon contributed positively to leaf expansion in this variety. In Bakhtawar, reductions were noted under T2, T3, and T4 by 15.3%, 11%, and 0.51%, respectively, indicating sensitivity to silicon and moderate salt stress. However, a significant improvement was observed under T6, where flag leaf area increased by 14.8%. This suggests that under high salinity, the addition of silicon alleviated stress effects and promoted leaf area expansion. Akbar showed mixed results. A pronounced increase in flag leaf area was noted under T4 (31.9%), followed by T6 (6.3%). Mild improvement occurred with Si alone (T2: 2%). In contrast, reductions were observed under T1 (12.3%) and T5 (7.5%), suggesting that Akbar responded more favorably to the combined treatment of moderate salt with Si (T4) (Figure 10). The number of grains per plant varied among the wheat varieties under different treatments. In Pirsabaq, the co-application of high salinity and silicon (T6) resulted in the greatest improvement (19.2%), while moderate salt with Si (T4) and Si alone (T2) caused reductions of 13.4% and 36.5%, respectively. T3 and T5 led to moderate increases (13.4% and 7.6%), indicating that certain salt levels may enhance grain set in this variety when not combined with Si. Bakhtawar showed a decline in grain number under most treatments. The highest increase was observed under T1 (9%), while reductions were found under T2 (19%), T3 (4%), T5 (17%), and especially T4 (42%), suggesting a negative interaction between Si and salt stress on grain formation in this variety. Akbar also showed a similar trend, with the highest increase under T1 (10%). Treatments T2, T3, and T4 led to progressive reductions of 16%, 4%, and 22%, respectively. A mild decrease (8%) occurred under T6. These results suggest that Akbar is moderately sensitive to both salt and silicon, particularly in combination (Figure 11).

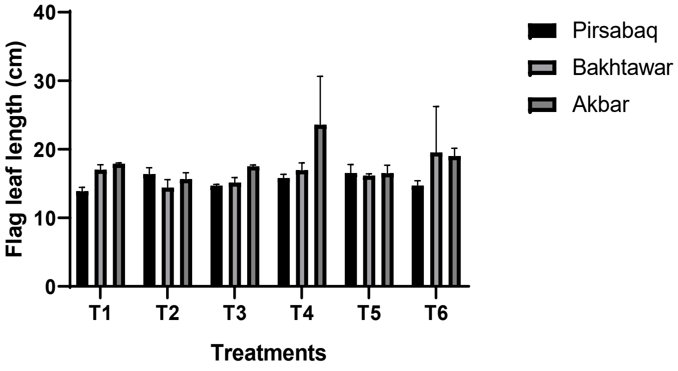

Figure 10: *Effect of silicon and salt on flag leaf area of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

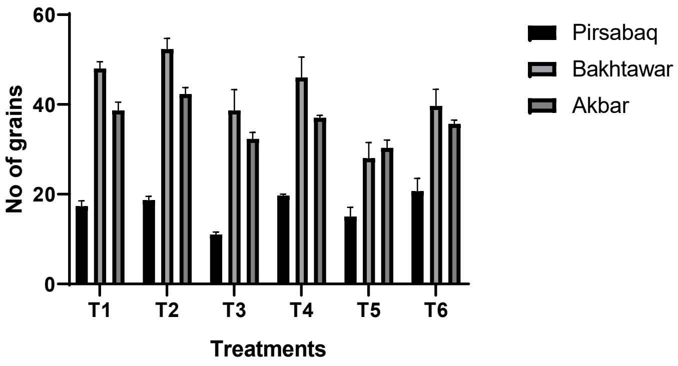

Figure 11: *Effect of silicon and salt on number of grains of wheat seedlings grown under laboratory conditions. Data calculations came from three replicates with their respective error bars. Different letters indicate significant differences among treatments ($p < 0.05$) based on factorial ANOVA.*

Discussion

Salinity is a major environmental stress that adversely impacts agricultural productivity by inhibiting plant growth, disrupting cellular metabolism, and reducing yield. High salt concentrations in soil, particularly sodium salts such as sodium chloride (NaCl), cause osmotic stress and ionic toxicity. These stressors interfere with water absorption, nutrient uptake, and plant physiological functions. Wheat (*Triticum aestivum* L.), a staple crop in many parts of the world, is particularly sensitive to salinity at early growth stages. In the present study, the negative impacts of salinity were evident through reduced plant height, stem thickness, leaf size, and yield-related traits. These results are consistent with earlier reports indicating that sodium chloride-induced salinity significantly decreases biomass accumulation, chlorophyll content, and photosynthetic efficiency in wheat (Fairoj *et al*., 2022). Although silicon (Si) is not classified as an essential nutrient for plants, it has gained considerable attention for its role in enhancing stress tolerance, particularly under abiotic stresses such as salinity, drought, and metal toxicity. In the present study, the application of silicon (Si) did not exhibit any pronounced positive or negative effects on plant growth parameters under salt stress. While silicon is widely reported to enhance plant tolerance to salinity by improving water uptake, reducing oxidative damage, and maintaining ionic balance (Imtiaz *et al*., 2016), its impact in the current experiment was marginal. Only in a few cases were slight improvements observed in specific parameters such as plant height or leaf area, but these were not consistent across all treatments or wheat varieties. The limited response to silicon application may be attributed to several factors, including genotype-specific sensitivity, silicon concentration, salt stress severity, and exposure duration. Previous studies have also reported variable effects of silicon on salinity. For instance, (Saleh and Oustan, 2017) noted that while silicon improved the growth of wheat under mild salinity, its effect diminished under high salt concentrations. Similarly, (Ali and Bijay-Singh, 2025) emphasized that the beneficial role of silicon is often contingent on environmental conditions and plant species. Therefore, it can be concluded that under the specific conditions of this experiment, silicon did not significantly ameliorate the adverse effects of salt stress, nor did it negatively impact the plants. These findings suggest that the role of silicon in mitigating salt stress may not be universally effective and warrants further investigation under varying agro-environmental settings. Enhanced vigor, leaf area, and biomass in Si-treated wheat could indirectly influence crop–weed interactions in saline fields. Improved canopy development may suppress weed emergence and growth through shading and resource competition. Additionally, variations in plant vigor could affect the efficacy and timing of herbicide applications, highlighting the potential agronomic relevance of Si supplementation for integrated weed management in salt-affected wheat agroecosystems.

Overall, these findings indicate that Si can partially alleviate salinity-induced stress, but its benefits are genotype- and stress level-specific. The results underscore the need for further research to optimize

Si application strategies under field conditions and to better understand the physiological mechanisms driving varietal differences in salinity tolerance.

Conclusions

The study revealed that salinity stress negatively affected most agronomic traits in wheat, though responses varied by variety and treatment. The combined application of silicon and moderate salt (T4) generally enhanced plant growth, especially in Bakhtawar and Pirsabaq. Bakhtawar showed the most significant improvement in traits such as spike length, flag leaf area, and grain content. Akbar was the most sensitive variety, showing limited positive response across treatments. Overall, silicon supplementation, particularly under moderate salinity, can mitigate stress effects and improve wheat performance.

Acknowledgments

The authors sincerely acknowledge the National Institute for Genomics and Advanced Biotechnology (NIGAB), National Agricultural Research Centre (NARC), Islamabad, for providing essential research facilities and technical support throughout the study. Special thanks are extended to the Department of Botany, Abdul Wali Khan University Mardan, for their assistance during experimentation and data analysis. The authors also express their deepest gratitude to Dr. Muhammad Amir Zia for his supervision, continuous guidance, and valuable suggestions that significantly improved the quality and outcomes of this research.

Novelty Statement

This study is novel in identifying the genotype-specific effects of exogenous silicon on wheat performance under controlled NaCl-induced salinity, which remains largely unexplored in Pakistani wheat cultivars. While several studies report the general role of silicon in salinity tolerance, our work uniquely compares three contrasting wheat genotypes under two distinct salinity levels, allowing us to differentiate varietal responsiveness. Additionally, the factorial design enables the simultaneous evaluation of silicon dose and salinity interaction, rather than analyzing them independently, which provides deeper insights into trait-specific stress recovery dynamics. The study therefore contributes new evidence showing that the benefits of silicon are not universal but strongly variety-dependent, emphasizing the need for customized nutrient-management practices in saline agriculture.

Author's Contribution

Abdullah: Conceived and designed the experiment, conducted data collection and analysis, and prepared the initial manuscript draft.
Muhammad Amir Zia: Supervised the overall research work, provided critical revisions, and ensured the scientific accuracy of the study.
Sartaj Aziz: Contributed to data interpretation and manuscript refinement.
Ihsan Ullah Khan and Ashtar Khan: Assisted in experimental setup and data validation.
Husnal Maab: Supported laboratory analysis and data organization.
Shah Zaib: Provided technical input and critical manuscript review.
Tanweer Kumar: Contributed to project coordination and overall review.
All authors read and approved the final version of the manuscript.

Funding
This research received no external funding.

IRB approval
Not applicable.

Informed consent statement
Not applicable.

Data availability statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Generative AI and AI-assisted technology statement
No generative artificial intelligence or AI-assisted tools were used in data analysis, result interpretation, or manuscript writing. All statistical analyses were performed using SPSS software, and all graphs were prepared using GraphPad Prism. The authors confirm that the entire scientific content was produced and validated manually by the research team.

Conflicts of interest
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential

conflict of interest.

References

Ali, A.M. and Bijay-Singh. 2025. Silicon: A crucial element for enhancing plant resilience in challenging environments. J. Plant Nutr., 48(3): 486-521. https://doi.org/10.1080/01904167.2024.2406479

Arif, Y., Singh, P., Siddiqui, H., Bajguz, A. and Hayat, S., 2020. Salinity-induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. Plant Physiol. Biochem., 156: 64-77. https://doi.org/10.1016/j.plaphy.2020.08.042

Attiq, W., Tayyab, Q. and Ali, Q., 2021. Salinity stress in crops: mechanisms and mitigation techniques using PGPR and silicon. Plant Environ., 2(1): 36-54.

Ashraf, M., and Saeed, M. M. 2006. Effect of improved cultural practices on crop yield and soil salinity under relatively saline groundwater applications. Irrigation and Drainage Systems, 20(1): 111-124.

Barão, L., 2023. The use of Si-based fertilization to improve agricultural performance. J. Soil Sci. Plant Nutr., 23(1): 1096-1108. https://doi.org/10.1007/s42729-022-01106-1

Batlle-Sales, J., 2023. Salt-affected soils: A sustainability challenge in a changing world. Ital. J. Agron., 18(2): 2188. https://doi.org/10.4081/ija.2023.2188

Dabravolski, S.A. and Isayenkov, S.V., 2024. The physiological and molecular mechanisms of silicon action in salt stress amelioration. Plants, 13(4): 525. https://doi.org/10.3390/plants13040525

Dhakal, A., Adhikari, C., Manandhar, D., Bhattarai, S., and Shrestha, S. 2021. Effect of abiotic stress in wheat: a review. Reviews In Food and Agriculture, 2(2), 69-72.

Fairoj, S.A., Islam, M.M., Islam, M.A., Zaman, E., Momtaz, M.B., Hossain, M.S. and Murata, Y., 2022. Salicylic acid improves agro-morphology, yield and ion accumulation of two wheat (*Triticum aestivum* L.) genotypes by ameliorating the impact of salt stress. Agronomy, 13(1): 25. https://doi.org/10.3390/agronomy13010025

Farooq, M., Zahra, N., Ullah, A., Nadeem, F., Rehman, A., Kapoor, R. and Siddique, K.H., 2024. Salt stress in wheat: Effects, tolerance mechanisms, and management. J. Soil Sci. Plant Nutr., 24(4): 8151-8173. https://doi.org/10.1007/s42729-024-02104-1

Ghadirnezhad Shiade, S. R., Fathi, A., Taghavi Ghasemkheili, F., Amiri, E. and Pessarakli, M. 2023. Plants' responses under drought stress conditions: Effects of strategic management approaches. A review. J. Plant Nutr., 46(9): 2198-2230. https://doi.org/10.1080/01904167.2022.2105720

Hasanuzzaman, M. and Fujita, M., 2022. Plant responses and tolerance to salt stress: Physiological and molecular interventions. Int. J. Mol. Sci., 23(9): 4810. https://doi.org/10.3390/ijms23094810

Houben, M., Vaughan-Hirsch, J., Pattyn, J., Mou, W., Roden, S., Martinez Roig, A. and Van de Poel, B., 2024. 1-Aminocyclopropane-1-carboxylic acid oxidase determines the fate of ethylene biosynthesis in a tissue-specific way to fine-tune development and stress resilience. bioRxiv [Preprint]. https://doi.org/10.1101/2024.02.01.578397

Imtiaz, H., Mir, A.R., Corpas, F.J. and Hayat, S., 2023. Impact of potassium starvation on uptake, transportation, photosynthesis, and abiotic stress tolerance. Plant Growth Regul., 99(3): 429-448. https://doi.org/10.1007/s10725-022-00925-7

Imtiaz, M., Rizwan, M. S., Mushtaq, M. A., Ashraf, M., Shahzad, S. M., Yousaf, B. and Tu, S., 2016. Silicon occurrence, uptake, transport and mechanisms of heavy metals, minerals and salinity enhanced tolerance in plants: A review. J. Environ. Manage., 183: 521-529. https://doi.org/10.1016/j.jenvman.2016.09.009

Islam, M. S., Nur-E-Alam, M., Iqbal, M. A., Khan, M. B., Al Mamun, S., Miah, M. Y., ... and Salam, M. A. 2024. Spatial distribution of heavy metal abundance at distance gradients of roadside agricultural soil from the busiest highway in Bangladesh: A multi-index integration approach. Environmental Research, 250, 118551. https://doi.org/10.1016/j.envres.2024.118551

Jones, R. and Patel, S., 2022. Factorial ANOVA and leaf-area estimation methods for wheat growth analysis. J. Agron., 15(2): 112-120.

Katel, S., Yadav, S. P. S., Khadka, A., Karki, N., and Neupane, S. 2023. Cereal import and consumption patterns in Nepal–Analysis of rice, wheat, maize, and millet: A review. Russian Journal of Agricultural and Socio-Economic Sciences, 139(7), 16-32.

Ludwiczak, A., Osiak, M., Cárdenas-Pérez, S., Lubińska-Mielińska, S. and Piernik, A., 2021. Osmotic stress or ionic composition: Which affects the early growth of crop species more? Agronomy, 11(3): 435. https://doi.org/10.3390/agronomy11030435

Murtaza, G., Qadir, A. A., Farooqi, Z. U. R., and Murtaza, B. 2023. Nutrient Depletion in Salt-Affected Soils and Yield Reduction. In Soil Constraints and Productivity (pp. 239-254). CRC Press. https://doi.org/10.1201/9781003093565-13

Pontigo, S., Ribera, A., Gianfreda, L., de la Luz Mora, M., Nikolic, M. and Cartes, P., 2015. Silicon in vascular plants: Uptake, transport and its influence on mineral stress under acidic conditions. Planta, 242(1): 23-37. https://doi.org/10.1007/s00425-015-2333-1

Rizwan, M., Ali, S., Ibrahim, M., Farid, M., Adrees, M., Bharwana, S.A. and Abbas, F., 2015. Mechanisms of silicon-mediated alleviation of drought and salt stress in plants: A review. Environ. Sci. Pollut. Res., 22(20): 15416-15431. https://doi.org/10.1007/s11356-015-5305-x

Saleh, J., Najafi, N. and Oustan, S., 2017. Effects of silicon application on wheat growth and some physiological characteristics under different levels and sources of salinity. Commun. Soil Sci. Plant Anal., 48(10): 1114-1122. https://doi.org/10.1080/00103624.2017.1323090

Shahid, M.A., Sarkhosh, A., Khan, N., Balal, R.M., Ali, S., Rossi, L. and Garcia-Sanchez, F., 2020. Insights into the physiological and biochemical impacts of salt stress on plant growth and development. Agronomy, 10(7): 938. https://doi.org/10.3390/agronomy10070938

Sirhindi, G., Bhardwaj, R., Kapoor, N. and Seth, C.S., 2025. Metalloids in biology: from function to toxicity. CRC Press, UK. https://doi.org/10.1201/9781032673592

Saleh, J., Najafi, N., and Oustan, S. 2017. Effects of silicon application on wheat growth and some physiological characteristics under different levels and sources of salinity. Communications in Soil Science and Plant Analysis, 48(10), 1114-1122. https://doi.org/10.1080/00103624.2017.1332213

Smith, J. and Khan, A., 2020. Crop–weed competition in saline wheat fields: Implications for management. Weed Sci., 68(4): 345-356.

Subedi, S. and Khadka, P. 2022. Impact of climate change on wheat productivity: A Review. Ecofeminism and Climate Change, 3(1), 68-71. https://doi.org/10.26480/efcc.01.2022.68.71

Syed, A., Sarwar, G., Shah, S.H. and Muhammad, S., 2021. Soil salinity research in 21st century in Pakistan: Its impact on availability of plant nutrients, growth and yield of crops. Commun. Soil Sci. Plant Anal., 52(3): 183-200. https://doi.org/10.1080/00103624.2020.1854294

Tubaña, B.S. and Heckman, J.R., 2015. Silicon in soils and plants. In: Silicon and plant diseases. Cham: Springer International Publishing. pp. 7-51. https://doi.org/10.1007/978-3-319-22930-0_2

Watson, D.J. 1947. Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. Annals of botany, 11(41), 41-76. https://doi.org/10.1093/oxfordjournals.aob.a083148