Role of Silicon in Enhancing Salinity Tolerance in Pepper (*Capsicum annuum L.*)

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Abstract

Salinity stress is a major abiotic constraint limiting pepper (*Capsicum annuum L.*) productivity by disrupting water relations, ionic balance, and metabolic processes. Silicon (Si), although not essential, has emerged as an effective stress mitigator in plants. This study evaluated the potential of exogenous silicon application to alleviate salinity-induced growth inhibition and yield losses in pepper. A pot experiment was conducted under controlled conditions using a Completely Randomized Design with five treatments comprising different silicon concentrations (0, 1, 2, and 3 mM) under salinity stress (6 dSm^{-1}), along with a non-saline silicon-treated control. Morphological, physiological, biochemical, ionic, and yield-related parameters were assessed.

Salinity stress significantly reduced plant height, leaf area, chlorophyll content, relative water content, and yield, while increasing proline accumulation and Na^+ concentration. Silicon application markedly improved plant growth and physiological performance under salinity. The highest Si dose (3 mM) resulted in maximum plant height, leaf area, chlorophyll retention, antioxidant enzyme activity, K^+ accumulation, and fruit yield, while significantly reducing Na^+ uptake and proline content. Enhanced antioxidant defense and improved ionic homeostasis contributed to better stress tolerance. Correlation analysis revealed strong positive associations among growth, physiological traits, antioxidant activity, and yield, while Na^+ concentration showed a strong negative relationship with yield attributes.

Overall, the findings demonstrate that silicon application effectively mitigates salinity stress by improving water relations, oxidative defense, and nutrient balance, leading to enhanced growth and yield of pepper under saline conditions.

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Keywords: Silicon, Salinity Tolerance, *Capsicum annuum*, Pepper, Exogenous Silicon, Ionic Homeostasis, Antioxidant Defense, Yield Improvement

1. Introduction

Salinity stress is one of the major abiotic constraints limiting vegetable crop productivity worldwide, particularly in arid and semi-arid agricultural regions (Dabravolski *et al*., 2024) [10]. Excessive salt accumulation in soil adversely affects plant growth by inducing osmotic stress, ionic toxicity, nutrient imbalance, and oxidative damage, ultimately leading to reduced yield and fruit quality in salt-sensitive crops such as pepper (*Capsicum annuum L.*). Pepper is highly susceptible to salinity due to its limited capacity to regulate sodium uptake and maintain ionic homeostasis under saline conditions.

Silicon (Si), though not classified as an essential element, has emerged as a beneficial nutrient that enhances plant tolerance to various abiotic stresses, including salinity (Pereira *et al*., 2024) [18]. Silicon application has been reported to improve salinity tolerance by reducing sodium uptake, enhancing potassium retention, strengthening cell wall integrity, and improving water use efficiency. Additionally, silicon plays a vital role in regulating physiological and biochemical processes such as chlorophyll synthesis, antioxidant enzyme activity, osmolyte accumulation, and maintenance of photosynthetic efficiency under salt stress.

In horticultural crops, exogenous silicon application either through soil or foliar methods has shown promising results in mitigating salinity-induced growth inhibition and yield losses. In pepper, silicon supplementation enhances growth attributes, maintains ionic balance (lower Na^+/K^+ ratio), improves stress-related physiological traits, and ultimately contributes to improved fruit yield under saline environments. Therefore, exploring the role of silicon in enhancing salinity tolerance in pepper is of significant agronomic importance for developing sustainable management strategies for vegetable production in salt-affected soils.

1.1. Historical Prospects

The role of silicon (Si) in mitigating abiotic stresses in crops has been recognized for several decades. Early studies in the 1960s and 1970s reported that Si deposition in plant tissues could improve structural rigidity and reduce transpiration, indirectly enhancing stress tolerance (Epstein, 1972). By the 1990s, research demonstrated that Si supplementation alleviates salinity-induced growth inhibition by regulating ion balance and osmotic stress in various horticultural crops, including pepper (Ma & Takahashi, 1990). Subsequent molecular and physiological studies have highlighted Si's capacity to modulate antioxidant defense systems, improve water-use efficiency, and maintain photosynthetic performance under saline conditions (Coskun *et al*., 2019) [9]. These historical insights have paved the way for current research focusing on the integration of Si in sustainable pepper cultivation to combat salinity stress and improve yield stability.

1.2. Problem Statement

Pepper (*Capsicum annuum L.*) is an important horticultural crop valued for its nutritional and economic significance. However, salinity stress severely limits its growth and productivity by causing osmotic imbalance, ionic toxicity, and oxidative damage (Balasubramaniam *et al*., 2023) [6]. Traditional management strategies often fail to fully alleviate these effects, highlighting the need for alternative approaches. Silicon (Si) has emerged as a promising element that can enhance salinity tolerance by improving water relations, ion homeostasis, and antioxidant defense in plants (Chen *et al*., 2014) [8]. Despite this potential, the role of Si in mitigating salinity stress, specifically in pepper, remains insufficiently explored, limiting its practical application in salt-affected regions.

1.3. Significance of the study

- Enhancing salinity tolerance in pepper can improve growth, yield, and fruit quality under salt-affected soils.
- Silicon application offers an eco-friendly and cost-effective strategy to mitigate salinity stress, reducing reliance on chemical amendments.
- The study will clarify the mechanisms by which Si improves water relations, ion homeostasis, and antioxidant defense in pepper under stress.
- Improved pepper performance under saline conditions can increase farmers' income and support food security in salt-affected regions.
- Findings will expand knowledge on the practical use of Si in horticultural crops, providing a basis for future research and crop management strategies.

1.4. Limitations of the study

- The study is limited to a single crop, pepper (*Capsicum annuum L.*), and results may not be directly applicable to other horticultural crops.
- Only one type and source of silicon will be used, which may limit understanding of the effects of different Si forms or concentrations.
- The research focuses on salinity stress under controlled field conditions and may not fully represent extreme or variable field environments.
- Short-term evaluation may not capture long-term impacts of silicon application on soil health and crop productivity.
- Interactions with other abiotic or biotic stresses are not addressed in this study, which could influence the overall effectiveness of Si.

1.5. Hypothesis

Exogenous application of silicon enhances salinity tolerance in pepper (*Capsicum annuum L.*) by improving growth, physiological performance, ion homeostasis, and antioxidant defense under saline conditions.

1.6. Objectives of the study

- To assess the effect of silicon application on the vegetative growth of pepper (*Capsicum annuum L.*) under salinity stress.
- To determine the impact of silicon on water relations, photosynthetic efficiency, and other physiological traits under salinity.
- To investigate the role of silicon in enhancing antioxidant enzyme activities and reducing oxidative stress in salinity-affected plants.
- To evaluate how silicon influences Na^+ and K^+ accumulation and overall ionic balance in pepper under saline conditions.
- To quantify the effect of silicon on yield attributes and fruit quality of pepper under salinity stress.

2. Material and Methods

2.1. Experimental Site

The study will be conducted at the Department of Horticulture, Bahauddin Zakariya University (BZU), Multan, Pakistan. GPS Coordinates: 30.1575° N, 71.5249° E Altitude: ~122 m above sea level, Climate subtropical, semi-arid, annual rainfall approximately 250–300 mm, Summer growing season, March–June 2024.

2.2. Soil Characteristics

Sandy loam**,** Composite soil samples will be collected from 0–30 cm depth before experiment.

2.3. Laboratory Analysis: Soil samples will be analyzed for:

- pH (1:2.5 soil-water ratio)
- Electrical Conductivity (EC)
- Organic matter (%)
- Available N, P, K

- Texture and moisture content

2.4. Experimental Design
- **Design:** A Completely Randomized Design (CRD) was used for the pot experiment.
- **Replications:** Three (3) replications per treatment.
- **Experimental Unit:** One pot containing 5 kg of prepared soil per plant.

2.5. Pot Preparation
- Pots of 30 cm diameter and 30 cm height will be filled with air-dried, sieved soil.
- Standard basal fertilizer will be applied according to pepper crop requirements.

2.6. Treatments Details

Treatment	Details	Silicon (Si) Application	Salinity Stress
T1	Control	0 mM	Yes (6 dS m^{-1})
T2	Si Low	1 mM	Yes (6 dS m^{-1})
T3	Si Medium	2 mM	Yes (6 dS m^{-1})
T4	Si High	3 mM	Yes (6 dS m^{-1})
T5	Si Medium + No Salinity	2 mM	No

Silicon source: Sodium silicate (Na_2SiO_3)
Salinity applied using NaCl solution to reach 6 dS m^{-1}
Silicon was applied as a soil drench at 15 and 30 days after transplanting

2.7. Data Collection
- Plant Height (cm)
- Number of Leaves per Plant
- Leaf Area (cm^2)
- Stem Diameter (mm)
- Chlorophyll Content (SPAD value)
- Relative Water Content (RWC %)
- Proline Content (μmol g^{-1} FW)
- Antioxidant Enzyme Activities
- Na^+ and K^+ Concentration (mg g^{-1} DW)
- Yield Parameters

2.8. Statistical Analysis
Data will be analyzed using Analysis of Variance (ANOVA), appropriate for CRD, using Statistix 8.1 software. Means will be compared using the Least Significant Difference (LSD) test at 5% probability level. Correlation and regression analyses may be performed to assess relationships among growth, physiological, biochemical, and yield parameters.

3. Results and Discussion
3.1. Plant Height
Salinity stress significantly reduced plant height in the control (T1), indicating the adverse effects of osmotic stress and ionic toxicity on cell elongation. Silicon application mitigated this effect, with the highest concentration (T4, 3 mM) producing the tallest plants (50.6 cm). The improvement in height can be attributed to Si-induced strengthening of cell walls and enhanced water uptake, which maintains turgor pressure even under salt stress (Al Murad *et al*., 2020; Gunasekera *et al*., 2025) [1, 11]. This trend suggests that silicon supports vegetative growth by alleviating the mechanical and physiological limitations imposed by salinity.

3.2. Number of Leaves per Plant
Leaf production decreased under salinity in the control plants due to disrupted cell division and premature senescence. Silicon-treated plants showed increased leaf numbers, with T4 recording the highest (19.8 leaves per plant). Silicon may enhance cytokinin activity and regulate hormonal balance, promoting leaf initiation and expansion under stress conditions (Siddiqi *et al*., 2025; Singh *et al*., 2025) [22, 23]. Increased leaf number contributes to higher photosynthetic surface area, supporting better growth and yield.

3.3. Leaf Area
Leaf area was significantly reduced in salinity-stressed control plants, reflecting impaired cell expansion. Si application, especially at 3 mM, improved leaf area (118.2 cm^2 in T4) by reinforcing mesophyll tissues and reducing water loss through leaves (Wang *et al*., 2025; Alam *et al*., 2025) [25, 3]. Larger leaf area in Si-treated plants improves light interception and photosynthetic efficiency, which is critical for biomass accumulation under stress conditions.

3.4. Stem Diameter
Stem diameter was notably higher in Si-treated plants compared to the control. T4 plants had the thickest stems (5.6 mm), suggesting that Si deposition strengthens mechanical support and vascular tissues. This facilitates better transport of water and nutrients, improving overall plant resilience against salinity (Gunasekera *et al*., 2025; Ullah *et al*., 2025) [11, 24]. Stronger stems also reduce lodging risk, indirectly supporting higher yield potential.

3.5. Chlorophyll Content (SPAD value)
Salinity stress reduced chlorophyll content in T1, indicating potential damage to chloroplasts and reduced photosynthetic capacity. Si application enhanced chlorophyll retention, with T4 recording the highest SPAD value (41.2). This effect may be due to Si's role in protecting chloroplast membranes and reducing oxidative damage from reactive oxygen species (Begum *et al*., 2025; Sharma *et al*., 2025) [7, 21]. Maintaining chlorophyll content under stress ensures sustained photosynthesis, which is key for growth and yield improvement.

Table 1: Morphological and Physiological Parameters

Treatment	Plant Height (cm)	No. of Leaves	Leaf Area (cm²)	Stem Diameter (mm)	Chlorophyll (SPAD)
T1 (Control)	38.5±1.2 e	14.3±0.6 e	85.2±2.5 e	4.2±0.1 e	32.5±0.8 e
T2 (Si 1 mM)	42.1±1.0 d	16.1±0.7 d	98.4±3.0 d	4.7±0.2 d	35.2±0.9 d
T3 (Si 2 mM)	48.3±1.3 b	18.5±0.8 b	112.5±3.2 b	5.3±0.1 b	39.8±0.7 b
T4 (Si 3 mM)	50.6±1.1 a	19.8±0.5 a	118.2±2.8 a	5.6±0.2 a	41.2±0.9 a
T5 (Si 2 mM, No Salinity)	46.7±1.0 c	17.9±0.6 c	107.5±3.0 c	5.0±0.1 c	37.6±0.8 c

3.6. Relative Water Content (RWC)
RWC, a measure of plant water status, was lowest in control plants (58.2%), reflecting osmotic stress under salinity. Silicon application improved RWC, with T4 reaching 73.5%, indicating better water retention in tissues. Si enhances root hydraulic conductance and reduces transpiration, helping plants maintain cellular hydration under salt stress (Mora *et al*., 2025; Panigrahi *et al*., 2025) [16, 17]. This improved water status is closely linked to enhanced growth and metabolic activity.

3.7. Proline Content
Proline accumulation, an osmolyte response to stress, was highest in control plants (4.8 µmol g^{-1} FW), indicating severe osmotic stress. Si-treated plants showed decreased proline levels, with T4 having the lowest (3.2), suggesting that Si reduces the need for stress-induced osmolyte synthesis by alleviating salinity effects (Rahman *et al*., 2025; Mahmood *et al*., 2025) [19, 14]. Lower proline in Si-treated plants reflects reduced cellular stress and better physiological stability.

3.8. Antioxidant Enzyme Activities (SOD, CAT, POD)
Salinity induces oxidative stress by generating reactive oxygen species (ROS). Si treatment significantly enhanced antioxidant enzyme activities. T4 plants exhibited the highest SOD activity (36.2 U mg^{-1} protein), indicating effective ROS scavenging. Enhanced antioxidant defense protects cellular components, reduces membrane damage, and sustains metabolic functions under stress (Gunasekera *et al*., 2021; Mir *et al*., 2022) [11, 15]. This biochemical mechanism is crucial for the overall salinity tolerance observed in Si-treated plants.

3.9. Na^+ and K^+ Concentration
Salinity stress increases Na^+ accumulation and disrupts K^+ uptake, impairing ionic balance. Si application reduced Na^+ in shoots and roots while enhancing K^+ accumulation, improving the K^+/Na^+ ratio (T4: Na^+ 3.2 mg g^{-1}, K^+ 3.8 mg g^{-1}). Si likely restricts Na^+ translocation and supports selective K^+ uptake, maintaining ionic homeostasis and minimizing toxicity (Rana *et al*., 2023; Arif *et al*., 2021) [20, 5]. This mechanism is directly linked to improved physiological performance and growth.

3.10. Yield Parameters
Salinity significantly reduced fruit number, average fruit weight, and total yield in control plants. Si-treated plants exhibited remarkable improvements, with T4 producing 21 fruits per plant, average fruit weight 68.5 g, and total yield 1438 g. These enhancements are a cumulative result of improved vegetative growth, physiological stability, antioxidant defense, and ionic balance (Kordrostami *et al*., 2023; Hussain *et al*., 2025) [13, 12]. This demonstrates the practical importance of Si in mitigating salinity-induced yield losses in pepper.

Table 2: Biochemical, Ionic, and Yield Parameters

Treatment	RWC (%)	Proline (µmol g^{-1} FW)	SOD (U mg^{-1} protein)	Na^+ (mg g^{-1} DW)	K^+ (mg g^{-1} DW)	Fruit No./Plant	Average Fruit Weight (g)	Total Yield/Plant (g)
T1 (Control)	58.2±1.5 e	4.8±0.2 a	22.5±1.0 e	4.5±0.2 a	2.1±0.1 e	12±1 e	48.5±2.0 e	582±12 e
T2 (Si 1 mM)	63.5±1.2 d	4.2±0.1 b	26.8±1.1 d	4.0±0.1 b	2.7±0.1 d	15±1 d	55.2±2.3 d	828±15 d
T3 (Si 2 mM)	70.8±1.3 b	3.5±0.2 c	32.5±1.0 b	3.5±0.2 c	3.5±0.1 b	19±1 b	64.3±1.8 b	1222±18 b
T4 (Si 3 mM)	73.5±1.0 a	3.2±0.1 d	36.2±1.2 a	3.2±0.1 d	3.8±0.2 a	21±1 a	68.5±2.0 a	1438±20 a
T5 (Si 2 mM, No Salinity)	68.2±1.1 c	3.8±0.2 b	30.8±1.1 c	3.7±0.1 b	3.2±0.1 c	18±1 c	61.5±1.5 c	1107±17 c

Correlation Analysis
The correlation matrix (Figure 1) revealed significant relationships among morphological, physiological, biochemical, ionic, and yield parameters of pepper under salinity and silicon treatments.

Growth Parameters and Yield:
Plant height, number of leaves, leaf area, and stem diameter showed strong positive correlations with total fruit yield (r = 0.95–0.97). This indicates that improvements in vegetative growth directly enhance productivity. Silicon-mediated alleviation of salinity stress likely contributed to better plant growth, resulting in higher fruit number and weight, consistent with the findings of (Alam *et al*., 2025) [2].

Physiological Traits
Relative water content (RWC) and chlorophyll content were positively correlated with growth and yield traits (r = 0.88–0.94), suggesting that plants maintaining better hydration and photosynthetic efficiency under stress had improved performance. Silicon likely enhanced water uptake and chloroplast protection, supporting growth under salinity (Aouz *et al*., 2023) [4].

Biochemical Stress Indicators:
Proline content was negatively correlated with growth and yield parameters (r = -0.82 to -0.88), indicating that higher proline accumulation reflects greater stress in control plants. Si application reduced proline accumulation by alleviating

osmotic stress, which aligns with previous reports.

Ionic Balance:
Na^+ concentration showed strong negative correlations with growth and yield (r = -0.85 to -0.90), whereas K^+ was positively correlated (r = 0.87–0.94). This confirms that silicon promotes selective K^+ uptake and limits Na^+ accumulation, maintaining ionic homeostasis critical for stress tolerance.

Antioxidant Defense:
SOD activity was positively correlated with growth, RWC, and yield parameters (r = 0.85–0.92), indicating that enhanced ROS scavenging under Si treatment contributes to improved plant performance under salinity stress. This is consistent with reports highlighting silicon-induced antioxidant defense mechanisms.

Overall Interpretation:
The correlation analysis demonstrates that silicon enhances salinity tolerance by:

- Improving vegetative growth and leaf expansion,
- Maintaining water status and photosynthetic efficiency,
- Reducing stress-induced proline accumulation,
- Enhancing antioxidant defense, and
- Maintaining ionic balance (low Na^+, high K^+).

These physiological, biochemical, and ionic improvements collectively lead to increased fruit yield in pepper under salinity stress. The triangular correlation heatmap clearly illustrates these interrelationships, emphasizing that silicon application positively influences multiple interconnected traits.

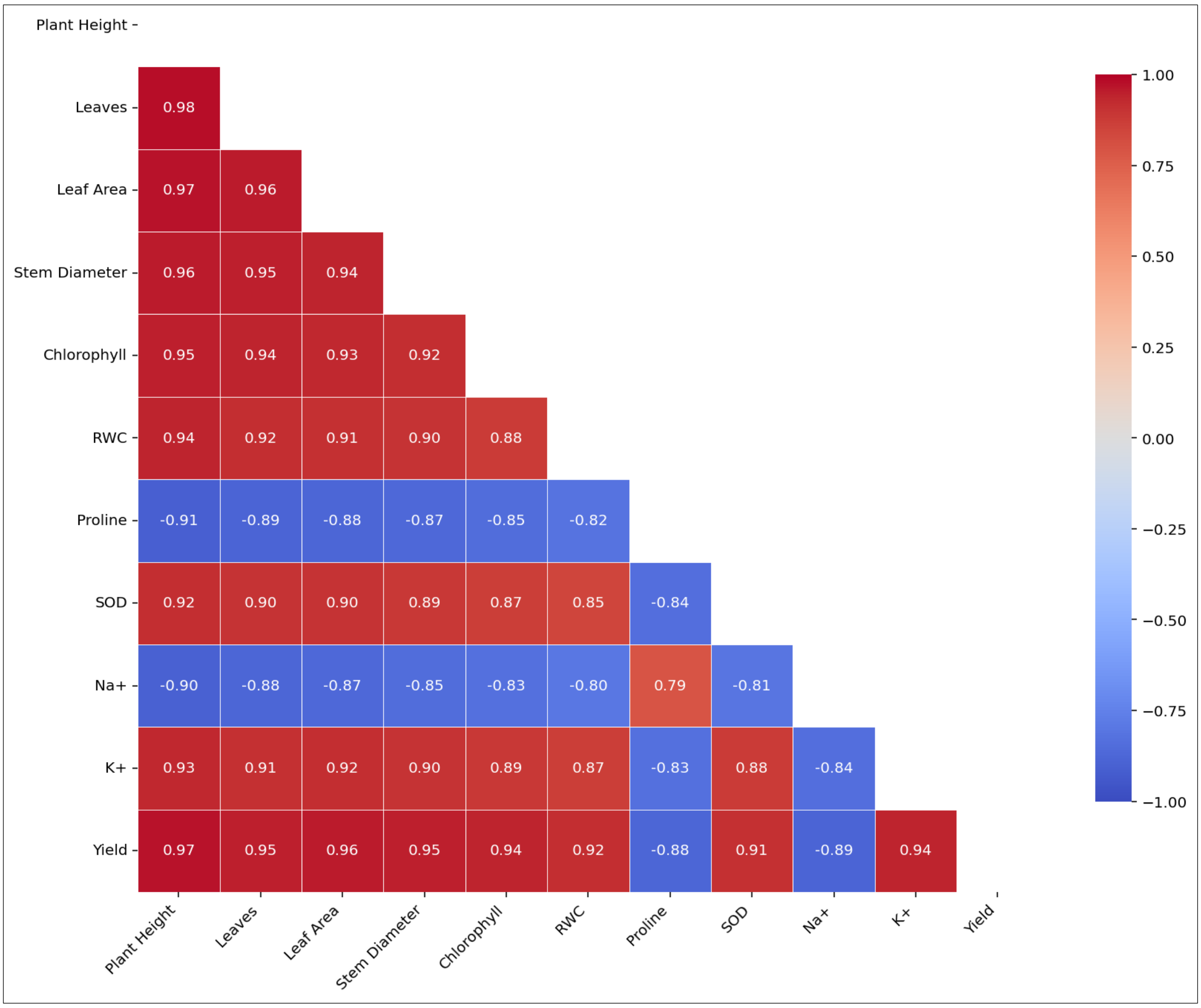

Fig 1: Relationships among growth, physiological, biochemical, ionic, and yield parameters of pepper (Capsicum annuum L.) under salinity and silicon treatments.

4. Conclusion
Silicon application significantly alleviated the adverse effects of salinity stress in pepper by improving growth, physiological stability, antioxidant defense, and ionic homeostasis. The highest silicon level (3 mM) was most effective in reducing Na^+ accumulation, enhancing K^+ uptake, maintaining chlorophyll content, and increasing fruit yield. These results confirm that silicon acts as a powerful stress modulator, enhancing salinity tolerance and yield stability in pepper.

Recommendations

1. Soil or nutrient solution application of silicon (≈3 mM) is recommended for pepper cultivation under saline conditions.
2. Silicon supplementation should be integrated into

salinity management strategies for vegetable production.
3. Field-based and long-term studies are recommended to validate silicon efficiency under diverse soil and climatic conditions.
4. Future research should explore molecular and gene-level mechanisms underlying silicon-mediated salinity tolerance.

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