Efficacy of Silicon Foliar Spray in Alleviating Salinity Stress in Sunflower (*Helianthus annuus* L.)

A THESIS

BY

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STUDENT ID: MS-230804

A Thesis (Course No. 081108 AGR 6116) Submitted to Agrotechnology Discipline in Partial Fulfillment of the Requirements for the Degree of Master of Science in Agronomy

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Dedicated

To

Our Beloved Parents

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February 2025 **The Author**

ABSTRACT

Sunflower is a popular oilseed crop worldwide including Bangladesh. This crop is well-fitted with high yield in salt-affected southwestern (SW) coastal soil in Bangladesh where many other crops of the country cannot be grown due to several abiotic stresses including salinity. Similarly, the yield of sunflowers is gradually reduced due to increased soil salinity. To reduce the salt effect the efficient technology is to flush out salts from the root zone. Due to lack of fresh irrigation water in this region, alternative options need to be searched to ameliorate salinity. Silicon (Si)-mediated salinity amelioration could be a potential option. Thus a pot experiment was conducted by spraying Si on sunflower leaf. The current study included two levels of salinity (0 and 8 dS m^{-1}) and four levels of Si (0, 0.3, 0.6, and 0.9 mM) foliar spray. The result revealed that leaf chlorophyll content index (SPAD value), plant biomass, seed yield, and yield attributes (head circumference, head parameter, seed number $head^{-1}$, 1000 seed weight, seed yield $plant^{-1}$) were reduced due to individual effects of salinity but these parameters were increased gradually due to application of Si and the highest seed yield was found in 0.9 mM Si foliar spray. The interaction of salinity and Si significantly affected head circumference, head diameter, and leaf chlorophyll content index, with the largest head circumference and diameter recorded in plants treated with 0.9 mM Si under control conditions, while the smallest values were observed in saline treatment with zero Si foliar spray, and the highest chlorophyll content index (42.3) found in zero salinity and 0.9 mM Si, which was statistically similar to saline treatment under 0.9 mM Si. Salinity increased shoot concentration of sodium (Na) and reduced the uptake of potassium (K), and Si; while Si application reduced the uptake of Na and increased the uptake of K and Si. The plant height and leaf number also reduced due to salinity and increased with the increasing levels of Si. The current study depicted that, salinity inhibited significantly sunflower growth and yield; however, the detrimental effects of salinity was mitigated by foliar application of Si. Thus, foliar application of Si at the rate of 0.9 or even 0.6 mM ameliorated the salinity effect in sunflower. Future research should also be done in the field.

Keywords: Salinity, Sunflower, Seed Yield, Ion Uptake, Silicon, Foliar Application.

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CHAPTER I

INTRODUCTION

Salinity stress is a pressing concern in agriculture, arising from the buildup of salt in the soil, and it presents a substantial global threat to crop production (Munns and Tester, 2008) including southwestern (SW) coastal Bangladesh (Bell et al. 2019; Paul et al. 2020; Karim et al. 1990). Around 20% of the world's cultivated land is impacted by salinity to varying degrees, resulting in significant reductions in both crop yield and quality (FAO, 2019). The major effects of salinity on crop plants are (i) osmotic stress and (ii) ion toxicity (Munns and Tester, 2008). All these effects are typically accompanied by oxidative stress (ROS) (Jovanović and Radović, 2021). As the availability of fresh water is scarce for flushing out salt from root zone in the salt affected coastal areas globally and so in SW Bangladesh, options for efficient utilization of the salinized land by cultivating suitable crops adopting new technologies, here foliar application of Si, should be investigated.

Silicon (Si) is a "quasi-essential metalloid" and stress element (Epstein, 1999) that alleviates several abiotic stresses including salinity (Coskun et al., 2016). Although abundant Si is available in the earth's crust (~29% by weight) in different forms, mostly they are unavailable to plants except for monosilicic acid, $Si(OH)_4$, with a typical concentration of 0.1 to 0.6 mM in soil water (Liang et al. 2015; Coskun et al. 2016). Within plants, Si ranges from 0.1 to 15% of dry weight depending on the species (Taiz and Zeiger, 2010). Silicon, as amorphous silica in cell wall, cell lumen, intracellular spaces and trichomes increasing tissue strength (Epstein, 1999). In salt-stressed crop plants, fertilization with Si increases water retention (Hurtado et al. 2020; Hattori et al. 2005) suppresses Na^+ uptake and translocation, stimulates K^+ uptake and K^+/Na^+ ratio (Liang, 1999). Despite the Si-mediated salt tolerance mechanisms are poorly understood but a number of literature proved that Si increases photosynthetic activity, leaf area and chlorophyll content and improving chloroplast structure (Savant et al., 1997; Liang, 1998; Rafi and Epstein, 1999; Tuna et al., 2008; Tahir et al., 2012; Haghighi and Pessarakli, 2013). Since, sunflower is an intermediate accumulator of Si (rice is the highest accumulator) (Tubana and Heckman, 2015; Liang, 2006), Si-fertilization under saline conditions might increase the salt tolerance and thus seed yield. In previous research in SW coastal soil with wheat, the soil application of Si showed no or little response despite the application rates were much higher: 0.1753 g Si kg^{-1} soil for rice (Syu et al., 2016; Das et al., 2021). The application of Si as foliar spray proved efficient in terms of Si absorption (Syu et al., 2016; Wang and Galletta, 1998) and yield increase. The available literature suggests that the application of exogenous foliar Si improves salinity tolerance in plants either by enhancing the activity of antioxidant enzymes or blocking Na^+ uptake and translocation, enhances the production of saturated fatty acid that increases the cell membrane stability against salinity (Khan et al., 2019). To ameliorate the salinity stress by foliar application of Si in sunflower no research has been done, to our knowledge despite sunflower has proved its potential to grow in SW region (Paul 2020, Paul 2021a). In soil supply of high amount of Si (0.3%) to sunflower in SW region, Kabir et al. (2024) found yield increase under 8 dS m^{-1} irrigation water salinity. As the soil supply requires high amount of Si, foliar spray of low concentration Si-mediated alleviation of salinity effect will be investigated in the current proposal.

In recent years, the application of silicon (Si) via foliar spray has garnered considerable attention for its potential to alleviate the adverse impacts of salinity stress on plants, including sunflower. Silicon, a naturally occurring element, has been recognized for its ability to enhance salt tolerance in various crop species. This enhancement is achieved through the positive modulation of several crucial physiological and biochemical processes within plants (Li et al., 2015). A large number of studies have concluded that the soil application of silicon (Si) had poor response in alleviating the salinity stress (Liang et al., 2015). On the contrary, evidences are increasing particularly in cereals and some cucurbits that the foliar spray of Si in ameliorating the salinity stress is much effective (Khan et al., 2019). Therefore, there is a knowledge gap regarding the potential benefits of silicon in enhancing sunflower's salinity stress tolerance. As the sunflower in the SW region is a potential crop during *Rabi* season and its yield reduces due to irrigation with saline water, we hypothesized that foliar fortification of Si in sunflower would be effective in alleviating the salinity stress.

The objective of the study was to investigate the alleviating effects of salinity by foliar spray of silicon (Si) on the sunflower to modulate the biomass yield and ion (Na, K, and Si) accumulation under saline conditions.

CHAPTER II

REVIEW OF LITERATURE

2.1 Role of Silicon in Plants Growth and Defense Mechanism

Silicon (Si) is the second most abundant element in the Earth's crust after oxygen. While not classified as an essential nutrient for plants, silicon is recognized as a beneficial element that enhances plant growth, development, and resilience to various stresses. Plants absorb silicon as silicic acid (H_4SO_4), which is then transported to different tissues. Within the cell walls, silicon forms a structural matrix, reinforcing the walls and strengthening plant structure.

Silicon (Si) is recognized for enhancing the structural integrity of plant cell walls, as it facilitates silica deposition, reinforcing cell walls with mechanical strength (Epstein, 1999). This reinforcement provides rigidity and acts as a physical barrier, bolstering the plant's resistance to both biotic and abiotic stresses.

Silicon's role in plant defense mechanisms has been widely researched (Ma and Yamaji, 2006). Accumulated silicon in plant tissues is associated with increased resistance to pathogens and pests, contributing to enhanced resilience against environmental stresses.

In addition, silicon significantly influences nutrient dynamics in plants (Liang et al., 2015). Research indicates that silicon enhances the absorption of essential minerals, such as potassium and iron, and regulates their transport within the plant, contributing to a balanced nutrient profile.

Si also mitigates abiotic stress factors, including salinity, drought, and heavy metal stress (Liang et al., 2007). This stress tolerance has positioned silicon as a valuable tool for sustainable agriculture, especially under challenging environmental conditions.

Silicon's impact on photosynthetic efficiency has gained attention as well (Guntzer et al., 2012). Studies indicate that silicon enhances chlorophyll synthesis and light capture, which improves photosynthetic performance and supports growth and productivity.

Research on silicon-mediated interactions between plants and microbes shows that Si promotes beneficial symbiotic relationships, particularly with mycorrhizal fungi, which influence nutrient cycling and overall plant health (Rodrigues et al., 2004). Understanding these interactions is essential for leveraging silicon in sustainable agriculture.

The agricultural application of silicon has shown promising effects on crop yield and quality (Ma and Takahashi, 2002). Silicon supplementation has improved productivity in crops such as rice, wheat, and sugarcane, suggesting potential economic and ecological benefits.

Additionally, silicon improves nutrient use efficiency by facilitating the uptake and utilization of nutrients like phosphorus, nitrogen, and potassium. It forms complexes with nutrients, enhancing their availability to plants (Ma and Yamaji, 2008).

The study examined the impact of potassium silicate (K_2O_3Si) on strawberry cultivars 'Kurdistan' and 'Paros' under sodium chloride salinity stress. Results showed K_2O_3Si could recover dry mass distribution of NaCl-stressed strawberry organs, increase Total Soluble Solid and Titratable Acidity, and increase phenols and flavonoids in Paros cultivar. This suggests silicon supply could maintain growth and yield under salinity (Yaghubi et al, 2019).

Finally, silicon enhances lodging resistance by increasing cell wall thickness and rigidity, helping plants withstand environmental challenges like wind, rain, and heavy fruit loads (Epstein, 1999; Ma and Yamaji, 2008).

2.2 Silicon and Abiotic Stress in Plants

Silicon (Si) is a prevalent element that has attracted attention for its role in enhancing plant resilience to abiotic stressors, such as drought, salinity, heavy metals, and extreme temperatures, which adversely affect growth and productivity.

Silicon is reported to increase plant tolerance to various abiotic stresses through several mechanisms, including regulation of antioxidant enzymes, osmotic adjustment, and modulation of gene expression (Liang et al., 2007; Zhu and Gong, 2013).

Drought stress disrupts plant water balance, leading to reduced growth and yield. Studies by (Chen et al., 2016) and (Gao et al., 2006) show that silicon application enhances water uptake and retention, thus reducing the harmful effects of drought on plants.

Salinity stress affects ion homeostasis in plants, causing cellular damage. Research by Kim et al. (2014) and Soundararajan et al. (2018) indicates that silicon helps regulate ion uptake and maintain osmotic balance, improving plant resilience under saline conditions.

Silicon (Si) has shown potential in alleviating water stress, especially under drought and salinity, by enhancing leaf transpiration control and root water absorption. Si application boosts root hydraulic conductance, partly by up-regulating aquaporin genes, which improves water transport efficiency. Additionally, Si raises potassium concentration in the xylem, aiding osmotic balance and water movement. Research suggests that Si primarily enhances plant water uptake rather than decreasing water loss, supporting crop drought resilience (Chen et al., 2018).

Heavy metal contamination poses a significant threat to plant health, but silicon can mitigate this by promoting sequestration of heavy metals and reducing their translocation within the plant (Shahid et al., 2014; Rana et al., 2023).

Extreme temperatures, whether heat or cold, can impair plant growth and development. Wahid et al. (2007) demonstrated that silicon application enhances thermo-tolerance and cold tolerance through various physiological and biochemical mechanisms.

2.3 Silicon and Salinity Stress in Plants

Salinity stress is a major abiotic factor limiting plant growth and productivity worldwide, affecting approximately 30% of irrigated land, and this is expected to increase due to climate change and unsustainable agricultural practices (Munns, 2005).

Silicon (Si), the second most abundant element in the Earth's crust, has been shown to effectively mitigate the adverse effects of salinity stress on plants (Hattori et al., 2005).

Plants absorb Si as silicic acid ($Si(OH)_4$), which is subsequently deposited in the cell walls of tissues such as the epidermis, xylem, and sclerenchyma (Epstein, 1999). In a study on soybean, the application of Si under salt stress conditions demonstrated improved growth, primarily through enhanced gibberellin levels and reduced levels of ABA and proline, indicating effective alleviation of NaCl stress (Lee et al., 2010).

Silicon (Si) has been shown to mitigate the effects of salinity on wheat (*Triticum aestivum L.*) and other crops. Si treatment significantly increased cell-wall Na^+ binding in salt-resistant and salt-sensitive wheat genotypes, leading to decreased shoot Na^+ concentration and enhanced shoot K^+: Na^+ ratios. This improved plant growth, with the salt-resistant SARC-1 genotype showing a 39% increase in shoot fresh weight and a 12% increase in root fresh weight (Saqib et al., 2008).

The study compared safflower and sunflower cultivars for salt tolerance during germination and seedling growth. Four cultivars and sunflower hybrids were tested at different NaCl levels. Safflower seedlings absorbed more Na+ than sunflowers, with safflower cultivars being more salt-tolerant (Kaya et al., 2019). Additionally, A study on eight sunflower cultivars under saline and non-saline conditions revealed differential responses to salt stress. Hysun-38 and Nstt-160 showed high salt tolerance, with better gas exchange, RWC, and proline levels. While salt stress reduced growth and gas exchange traits, it increased proline and Na^+ concentrations, with the leaf K^+/Na^+ ratio emerging as a key parameter for assessing salt tolerance (Shahbaz et al., 2011).

Research highlights that high salinity disrupts essential physiological processes, stunting growth and productivity. Silicon supplementation has emerged as a valuable approach to counter these effects by influencing plant resilience. A review by Dhiman et al. (2021) emphasized the impact of Si on physiological and biochemical processes affected by salinity, illustrating how Si uptake and accumulation enhance plant responses through omics approaches (transcriptomics and proteomics) that reveal Si's role in regulating phytohormonal balance and antioxidant responses.

Experimental findings with rice plants showed that Si application within the root zone significantly boosted growth compared to control plants under salinity stress. This treatment reduced sodium accumulation, electrolyte leakage, and lipid peroxidation. Enzymatic antioxidant responses, such as catalase, peroxidase, and polyphenol oxidase, were lower in Si-treated plants than in controls, suggesting that prolonged Si supplementation modulates both phytohormonal and antioxidant defense responses, thus enhancing salt tolerance (Kim et al., 2014).

This study explored the effects of exogenously applied silicon (Si) on wheat growth and physiological traits under sodium chloride salinity stress. Two wheat genotypes, SARC-3 (salt tolerant) and Auqab 2000 (salt sensitive), were grown with and without 2 mM Si in nutrient solutions containing either 0 or 100 mM sodium chloride. Results showed that salinity stress significantly reduced shoot and root biomass, but Si application increased both dry weights, plant water content, and reduced Na^+ concentrations. Additionally, Si improved shoot growth, chlorophyll content, and membrane permeability under 150 mM sodium chloride stress by enhancing water content and maintaining ion balance in the shoots (Tahir et al., 2012).

Another study examined the impact of silicon (Si) in the nutrient solution on durum wheat and bread wheat under salt stress, utilizing a 2×2 factorial design with varying NaCl and Si concentrations. High NaCl levels were found to reduce biomass and chlorophyll content, but Si application at both tested concentrations alleviated these negative effects and lowered sodium levels in plant tissues. Additionally, bread wheat exhibited greater salinity tolerance than durum wheat, with Si treatments improving calcium and potassium concentrations, although these levels remained lower than those in control plants (Tuna et al., 2008).

Si has been effective in improving salt tolerance across various crops, including rice, wheat, barley, and maize (Hattori et al., 2005). The effectiveness of Si in alleviating salinity stress varies with plant species, application methods, and salinity levels.

Similarly, research by (Hamayun et al., 2010) on soybeans indicated that Si application mitigated salt-induced growth inhibition and corrected plant hormone imbalances. The mechanisms underlying Si-mediated salinity tolerance involve complex interactions that regulate ion uptake, water balance, and antioxidant defense systems, making Si an integral component in enhancing plant resilience under salt stress.

2.4 Foliar and Soil Application of Silicon in Plants

Silicon primarily exists in soil as insoluble oxides or silicates, with soluble silicic acid concentrations between 0.1 and 0.6 mM. The results showed that foliar applications of silicic acid significantly increased grain and straw yields compared to the control, with the 2 and 4 ml L^{-1} treatments enhancing yields, while 8 ml L^{-1} resulted in a decrease. The study concludes that applying silicic acid at 4 ml L^{-1} alongside half the pesticide dosage effectively improves yields and silicon content in wetland rice (Prakash et al., 2011).

In another experiment, rice was cultivated in two types of soils, each with varying capacities for silicon retention and different arsenic (As) levels. In this study, three different application rates of silicon (as sodium silicate) were used on rice plants through two methods: (1) foliar application and (2) soil application. Different foliar applications of silicon (Si) did not significantly affect Si concentrations in the shoots or influence the growth and arsenic (As) accumulation in rice seedlings. The study suggests that while foliar Si applications do not reduce As accumulation, moderate soil applications of Si can effectively decrease As uptake in rice seedlings (Syu et al., 2016).

Si application method plays an important role in Na^+ detoxification by modifying the antioxidative defense mechanism, which could actively mediate some important physiological and biochemical processes and helps to increase the shoot biomass production in sorghum and sunflower plants under salt stress (Hurtado et al., 2020).

Hurtado et al. (2021) further showed that in sorghum, root Si application was most effective, while a combined root and foliar approach benefited sunflowers. These Si treatments appear to enhance plant resilience to Na+ toxicity, supporting growth under salt stress by optimizing ion balance.

Soil salinity affects plant growth and yield through osmotic stress, toxicity, and nutritional imbalance. To improve salinity tolerance, gene introduction, breeding methods, and mineral nutrient regulation are used. Silicon mediates salinity tolerance, improving plant defense and performance against biotic stress (Ali et al., 2012).

2.5 Mechanism of Silicon-Mediated Stress Alleviation in Plants

Understanding silicon's stress-alleviating effects begins with its uptake and transport in plants. Silicon is absorbed as monosilicic acid from the soil solution via root uptake mechanisms. Transporter proteins, like Lsi_1 and Lsi_2 in rice, facilitate silicon uptake (Ma and Yamaji, 2006). Once inside the plant, silicon travels through the xylem to various tissues and organs. The regulation of silicon transporters is crucial in determining silicon accumulation levels in plant tissues, which directly influences its stress-mitigating efficacy.

Silicon's influence on cellular and molecular responses to stress involves complex interactions across multiple signaling pathways and gene expression cascades. Silicon induces the expression of stress-responsive genes, including those involved in synthesizing osmoprotectants like proline and glycine betaine, collectively enhancing stress tolerance in silicon-treated plants (Li et al., 2015).

On a structural level, silicon-mediated stress alleviation is associated with morphological and physiological adaptations. Silicon deposition in cell walls enhances cell rigidity and reduces transpiration rates, leading to improved water use efficiency under drought conditions (Coskun et al., 2019). Silicon accumulation in epidermal cells also forms a physical barrier against pathogens, providing a first defense line against biotic stressors. These structural adaptations, along with changes in root architecture, bolster plant resilience under environmental stress.

Silicon also plays a role in nutrient uptake and assimilation, adding another layer to its stress-relief mechanisms. Silicon enhances the uptake of essential nutrients, like phosphorus and potassium, by affecting their availability in the rhizosphere (Gunes et al., 2008).

Additionally, silicon helps correct nutrient imbalances caused by stress, maintaining an optimal nutrient status in plants. The interplay between silicon and other nutrients highlights the importance of a holistic approach to nutrient dynamics in stress responses (Ali and Bijay-Singh, 2024).

Studies in cucumber (*Cucumis sativus*) have shown that silicon mitigates heavy metal stress by reducing metal uptake and translocation, which in turn minimizes oxidative damage and maintains plant health under toxic conditions (Liang et al., 2015).

2.6 Silicon and Stress-Related Research in Coastal Areas

In the coastal region of Dumki upazila, Patuakhali, Bangladesh, researchers investigated optimal silicon (Si) sources and application rates to boost rice yield and Si efficiency in the Ganges delta soil. A 2021 study used a split-plot design across two phases to test three Si sources and seven rates. Calcium silicate emerged as the preferred source, with an optimal rate of 24 kg Si ha^{-1}. Silicon application improved Si content, uptake, and chlorophyll levels in rice, leading researchers to recommend calcium silicate for Ganges delta soils. The study pointed out the scarcity of research on Si use, advocating further exploration of different sources and application rates, including industrial byproducts (Haque et al., 2022).

Field experiments have also examined the impact of foliar-applied soluble silicic acid on wetland rice growth and yield. Results showed that foliar silicic acid at 2 and 4 ml per liter increased grain and straw yields, while 8 ml per liter reduced yields. Notably, a combination of foliar spray at 4 ml per liter with half the recommended pesticide dose resulted in the highest yields, with enhanced Si levels in grain and straw compared to control groups (Prakash et al., 2011).

During the wet season of 2021, research at Patuakhali Science and Technology University, Bangladesh, demonstrated the positive effects of Si on rice leaf erectness in the coastal region, which improved grain yield. The study compared Si doses of 0 and 100 mg kg^{-1} of soil across four rice varieties, with calcium silicate as the Si source. Under Si-amended conditions, Moulata and BRRI dhan77 varieties showed the highest Si responsiveness, with Moulata displaying substantial increases in shoot dry weight, root volume, leaf area, and Si uptake (Haque, Hoque, et al., 2023).

In another coastal study on pigeonpea (*Cajanus cajan*) in the U.S. Southern Coastal Plain, researchers found that Si applications, specifically calcium silicate, mitigated soil acidity and enhanced phosphorus availability. This led to improved plant-available water, increased growth, and better leaf erectness, crucial for light capture and growth (Owino-Gerroh et al., 2005).

In a dry-season field experiment in 2021 and 2022 with maize (Don-111 variety) in Bangladesh's eastern Ganges delta, Si application (20 kg Si ha^{-1}) combined with varying NPK fertilizer levels significantly increased yields. In 2021, yields rose by up to 17.9%, and in 2022 by up to 28.0%, with the most notable improvements at lower NPK rates. Si application enhanced growth, yield, and silicon content, proving beneficial for maize cultivation in the region (Haque, Mobaswera, et al., 2023).

In Australia's eastern Queensland coastal plain, where 95% of the country's sugarcane is grown, studies found that prolonged cultivation (up to 130 years) has led to reduced soil silicon levels due to weathering and leaching. This coastal region's unique topography and high rainfall exacerbate Si depletion, highlighting the need for soil Si replenishment to sustain sugarcane production (Berthelsen et al., 2001). These studies emphasize Si's role in enhancing stress resilience and productivity in coastal agriculture, underscoring the importance of further Si research for optimizing crop yield and soil health.

2.7 Silicon Mediated Researches in Bangladesh

In the Rabi (dry) season of 2019, a controlled pot experiment was conducted at Patuakhali Science and Technology University in Bangladesh to evaluate the impact of silicon (Si) on rice growth under salt-stress conditions. Using a two-factor randomized complete block design with three replications, the experiment included salinity concentrations of 0 and 6 dS/m as the first factor and four levels of Si (0, 2, 4, and 8 mM) as the second factor. Sodium chloride and silicic acid were used as salt and Si sources. Salinity stress negatively affected rice growth, reducing height, tillers, and shoots' weights. Si application at different concentrations enhanced growth, with 8 mM Si application showing the most efficacy (Sultana et al., 2021).

In a separate container experiment conducted at the Bangladesh Institute of Nuclear Agriculture in Mymensingh from January to May 2012, researchers explored the effects of various Si application levels on the growth, yield-contributing factors, and grain yield of BINA Dhan-8 rice. Silicon was applied through calcium silicate ($CaSiO_3$) at rates of 0, 5, 7.5, 10, 12.5, and 15 grams per pot, utilizing a Completely Randomized Design (CRD) with three replications. The findings revealed that different levels of Si application significantly enhanced the number of panicles, filled grains per panicle, 1000-grain weight, and grain yield per pot (Akter et al., 2017).

Additionally, a review article discussed recent advancements in the application of Si to improve crop growth, yield, soil nutrient availability, and drought tolerance. The review emphasized Si's critical role in enhancing crop development and productivity, especially under challenging environmental conditions. Silicon contributes to the increased availability and accumulation of both macronutrients (such as nitrogen, potassium, calcium, and sulfur) and micronutrients (including iron and manganese). Furthermore, it enhances drought resistance by improving water use efficiency and minimizing water loss during transport. Consequently, the application of Si emerges as a vital factor in boosting overall crop productivity, with the review identifying existing gaps in understanding and proposing future research directions based on the study's insights (Rea et al., 2022).

Another experiment demonstrated that Si plays a crucial role in detoxifying arsenic (As) in wheat under As stress. The addition of Si significantly improved morphophysiological traits, total protein content, and membrane stability compared to As-stressed plants.. This suggests that Si assists in sequestering As in roots, thereby reducing its translocation to shoots. Additionally, increased activities of catalase, peroxidase, and glutathione reductase in roots indicate an active role in scavenging reactive oxygen species, protecting wheat from As-induced oxidative damage (Hossain et al., 2018).

In another study, rapeseed (*Brassica napus*) seedlings were treated with exogenous Si to examine changes in antioxidant defense and glyoxalase systems. The results indicated that Si improved plant tolerance to salinity stress by enhancing both antioxidant defense and glyoxalase systems, leading to reduced oxidative damage and lower levels of methylglyoxal (Hasanuzzaman et al., 2018).

In a pot experiment, sunflower crops were grown in saline conditions with Si added to the soil. Four levels of Si (0, 0.1, 0.2, and 0.3 g Si kg^{-1} soil) and two salinity levels (0 and 8 dS m^{-1}) were present in the current investigation. The study suggests that salinity reduces sunflower growth and yield, but Si application can alleviate this effect. Applying more than 0.3 g Si kg^{-1} soil might suppress the salinity effect, increasing seed yield (Kabir et al., 2024).

CHAPTER III

MATERIALS AND METHODS

3.1. Experimental site

The experiment was carried out at Professor Dr. Purnendu Gain Field Laboratory of Agrotechnology Discipline, Khulna University, Khulna. The experimental site was located under the agro-ecological zone Ganges Tidal Floodplain (AEZ-13).

3.2. Planting material

Hybrid sunflower (*Helianthus annuus* L.) variety Hysun 33 was used as plant material.

3.3. Silicon (Si) source

The source of Si was silicic acid (powder form, AR grade).

3.4. Experimental treatment

This is two factor experiment-

Factor A: Salinity of irrigation water with zero (0) (salinity ~1) and 8 dS m^{-1}.

Factor B: Foliar spray rates of Si: 0, 0.3, 0.6 and 0.9 mM.

There were three replications thus the treatment combinations were 24 (24 pots).

3.5. Experimental design

The experiment was laid out in two factors completely randomized design (CRD).

3.6. Collection and preparation of pot soil

The experimental soil was collected from the field of saline area (Dacope, Khulna). After drying and sieving the soil, one-third of nitrogen and all other fertilizers were mixed with soil and the remaining two-third of N were applied in equal splits after 20 and 40 days of sowing seed. The experimental plastic pots were filled with the 11-kg soil on 22nd November 2023. Two sunflower seeds were sown on 23rd November, 2023 in each pot and irrigated immediately with fresh water. The pots was placed under a transparent plastic shed. After emergence (15 days after sowing, on 8th December, 2023) thinning was done to keep one healthy plant per pot.

3.7. Application of fertilizer

During pot soil preparation for Pot^{-1}, fertilizers were applied as follows: Urea at 0.7366 g (150 kg ha^{-1}) with a first split of 0.25 g, TSP at 0.147 g (30 kg ha^{-1}), MOP at 0.196 g (40 kg ha^{-1}), and cow dung constituting 30-40% of the total soil. Saline solutions (made from NaCl) were applied starting from low concentration: 2 dS m^{-1} after 1 week of emergence, 4 dS m^{-1} after 2 weeks of emergence, 6 dS m^{-1} after 3 weeks of emergence, and 8 dS m^{-1} after 4 weeks of emergence. The initial field-soil salinity was taken into account during the preparation of saline irrigation water. However, the saline-pot was irrigated with 8 dS m^{-1} water after 4 weeks to maturity. The zero salinity treatment was irrigated by reverse osmosis (RO) water. The treatment Si spray with different concentrations was applied four times: at 15, 30, 45, and 60 days after sowing (DAS). During spraying, care was taken to prevent reaching Si-spray water to the surface of pot-soil (e.g., covering pot surface by polythene).

3.8. Data collection

Data were collected on plant height, leaf number, shoot and root dry weight, yield attributes (head circumference, head diameter, filled seed number, seed weight,1000 seed weight) and seed yield, Na, K and Si concentration in shoot.

Growth parameters

Plant height (cm) was measured using the measuring scale from the base to the tip of each plant in each pot. The number of leaf $plant^{-1}$ was recorded and counted several times at 32 DAS, 48 DAS, 64 DAS, and 80 DAS. Leaf chlorophyll content was recorded through the SPAD 502Plus chlorophyll meter from each plant's leaves (fully expanded third leaf from the top) at 50 DAS, 65 DAS and 80 DAS. We gathered dry weight from every plant after harvesting. Initially, we used a sickle to cut the stem at the soil level. After that, water flow was used to remove the root from the soil. All plant parts was first sun-dried before being dried for 72 hours at 60°C. Then, an electric balance used to weigh the dried plants.

Seed yield and yield contributing parameters

The number of filled seeds per plant was collected and counted from the sunflower head, while total number of unfilled seeds was also recorded from each head to determine the untied seeds. Head circumference and head diameter (cm) were measured prior to harvesting using measuring tape. Seed weight was recorded separately pot-wise and expressed as seed yield with g $plant^{-1}$. After sun drying, an electric balance weighed 1,000 grains from each treatment.

Determination of nutrient content (Na, K, Si)

For determination of shoot Na^{+}, K^{+}, and Si plant shoot (harvested at maturity) was dried at 70 °C in a forced draft oven for 3 days and then ground to powder. Fine ground samples of shoot were digested in di-acid mixture of nitric and perchloric acids (3 : 1) at 150° C for 2 h. Na^{+} and K^{+} in shoot were determined using a flame photometer (Jenway PFP-7, Germany). The Si in the digested solution was determined by the colorimetric molybdenum blue method at 600 nm (Ma, 2004).

3.9. Statistical analysis

The collected data were analyzed in two-way ANOVA following CRD using the statistical program 'Statistix 10'. The differences between treatment means was separated by Duncun's multiple range test (DMRT).

CHAPTER IV

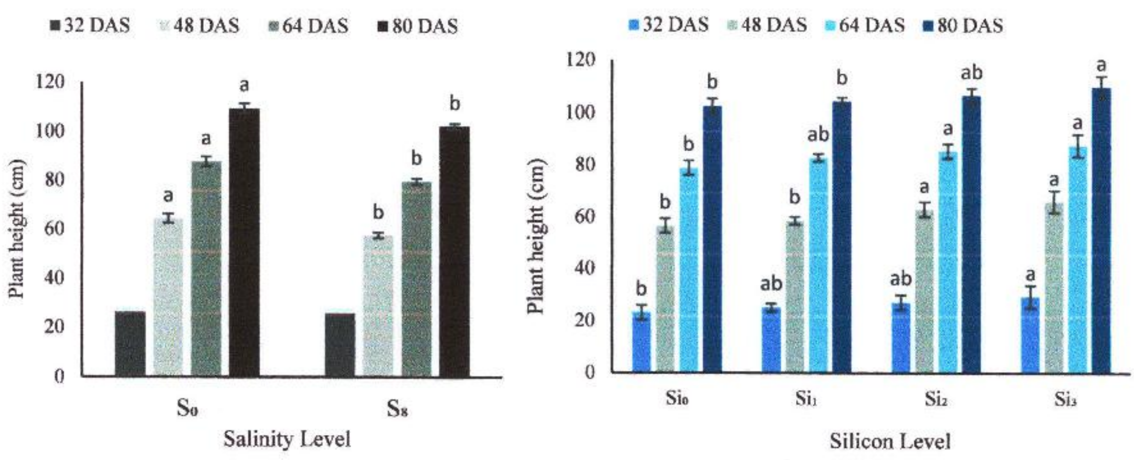
RESULT

4.1 Plant height

Due to saline water irrigation, plant height was not influenced at 32 days after sowing (DAS) but it was varied significantly due to salinity at 48 DAS (at head formation stage), 64 DAS (at 50 % flowering stage), and 80 DAS (at full flowering stage) (Fig. 1. a). At 48 DAS, 64 DAS, and 80 DAS, the plant height was significantly decreased respectively by 6.8 cm, 8.1 cm, and 7.3 cm due to salinity, which was 10%, 9%, and 6% reduction from that of control (zero salinity).

Due to Si application, the plant height was varied significantly at 32 DAS, 48 DAS, 64 DAS, and 80 DAS (Fig.1.b). At 80 DAS the maximum plant height (109.9 cm) was found in 0.9 mM Si which decreased gradually with the decrease in Si levels and lowest (23.2 cm) was found at 32 DAS from zero Si level.

The interaction of salinity and silicon on plant height was found non-significant thus data was not shown.

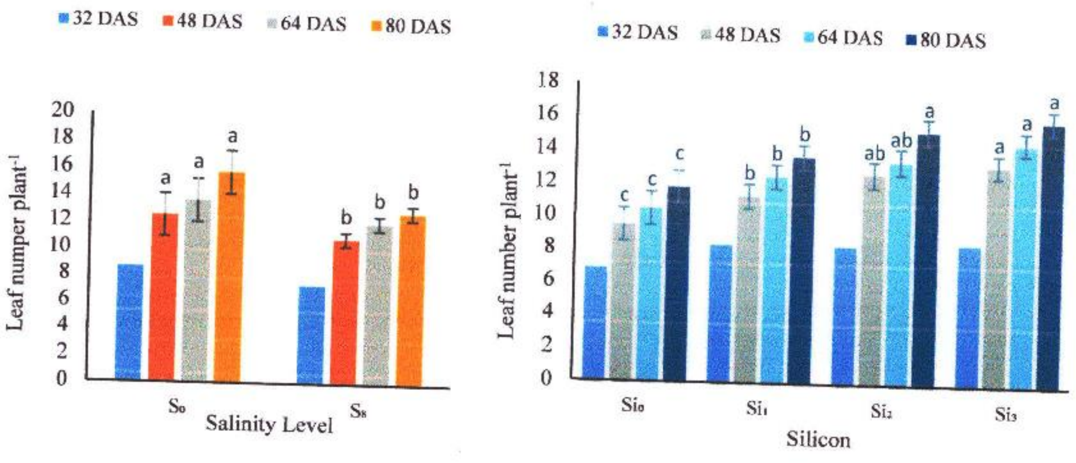


(a) (b)

Fig. 1. Plant height of pot grown sunflower as affected by salinity (a) and silicon (b). Here, S_0 and S_8 indicate salinity zero and 8 dS m^{-1} while Si_0, Si_1, Si_2, and Si_3 indicate 0, 0.3, 0.6, and 0.9 mM Si foliar spray. Different letters on the bar indicate the means are statistically different (a) between salinity; (b) among silicon. Vertical bars indicate mean ±SE.

4.2 Leaf number plant^{-1}

Due to salinity leaf number plant^{-1} was varied significantly at 48 DAS, 64 DAS, and 80 DAS, but it was not varied significantly at 32 DAS (Fig. 2.a).The highest leaf number was obtained from the control (zero salinity). At 80 DAS, leaf number decreased by 2.9 cm due to salinity, which was an 18% reduction from that of the control (zero salinity). Due to silicon, the maximum leaf number of plant^{-1} was found at 0.9 mM Si compared to that of control (Fig. 2.b). Silicon application increased the leaf number under non-saline conditions at 80 DAS (full flowering stage). The interaction of salinity and Si on leaf number was found non-significant thus data was not shown.



(a) (b)

Fig. 2. Leaf number plant^{-1} of pot grown sunflower as affected by salinity (a) and silicon (b). Here, S_0 and S_8 indicate salinity zero and 8 dS m^{-1} while Si_0, Si_1, Si_2, and Si_3 indicate 0, 0.3, 0.6, and 0.9 mM Si foliar spray. Different letters on the bar indicate the means are statistically different (a) between salinity; (b) among silicon. Vertical bars indicate mean ±SE.

4.3 Leaf chlorophyll content index

The experiment showed that there were significant differences of SPAD value at several days after sowing (Table 1). SPAD value (CCI) was decreased by 16%, 10% and 15% compared to control (zero salinity), at 50 DAS, 65 DAS, and 80 DAS, respectively.

Due to Si application, SPAD value (CCI) was varied significantly at 50 DAS, 65 DAS, and 80 DAS (Table 2). At 50 DAS the maximum SPAD value (CCI) (57.4) was found in 0.9 mM Si which decreased gradually with the increase in Si levels and lowest (35.7) was found at 80

Table 2. SPAD value (CCI) of sunflower at different days after sowing (DAS) as affected by silicon

	SPAD value (CCI)		
Silicon (m M)	50 DAS	65 DAS	80 DAS
0	47.5 b	39.0 b	35.7 c
0.3	49.4 b	41.5 ab	36.7 c
0.6	50.9 b	43.8 a	39.3 b
0.9	57.4 a	44.6 a	41.5 a
CV (%)	5.6	6.8	5.33
P value	<0.01	<0.05	<0.01
SE (±)	2.2	1.8	0.98

Different letters in a column indicate the means are statistically different according to Duncan's Multiple Range Test ($p \leq 0.05$). Here, CV = Coefficient of variation, SE= Standard Error.

Table 3. SPAD value (CCI) of sunflower at 50 DAS as affected by the interaction of silicon (Si) and salinity

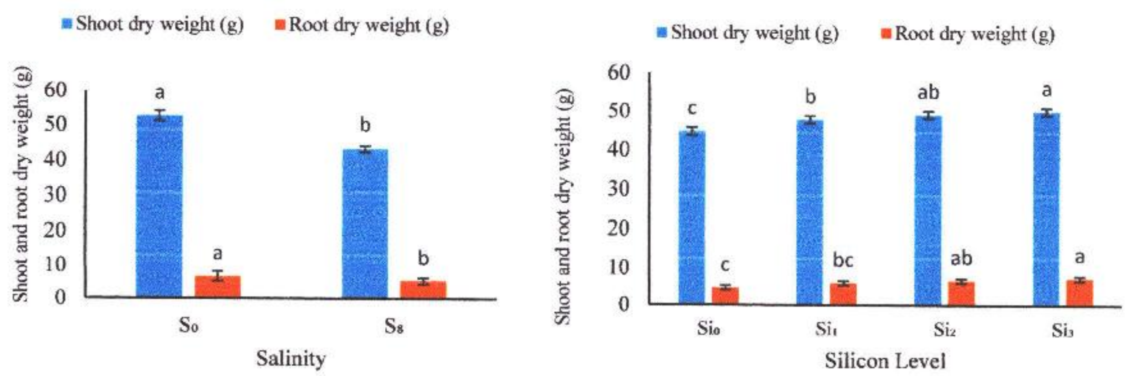
Sal x Si	50 DAS
$S_0 Si_0$	40.6 a
$S_0 Si_1$	40.9 a
$S_0 Si_2$	42.2 a
$S_0 Si_3$	42.3 a
$S_8 Si_0$	30.7 c
S_8Si_1	32.5 c
S_8Si_2	36.5 b
S_8Si_3	40.6 a
CV (%)	5.33
P value	<0.01
SE (±)	1.4

Different letters in a column indicate the means are statistically different. Here, S_0 and S_8 indicates salinity while Si_0, Si_1, Si_2 and Si_3 indicate 0, 0.3, 0.6 and 0.9 mM Si foliar spray.

4.4 Shoot and root dry weight (g)

Salinity reduced shoot and root dry weight significantly (Fig. 3. a). Shoot weight was reduced by 18% due to application of salinity (8 dS m^{-1}) while root weight was reduced by 19% compared to that of control (0 salinity).

Due to application of Si the shoot and root dry weight was increased significantly and the highest values of shoot and root were found when Si was applied at the rate of 0.9 mM foliar spray (Fig. 3. b). Silicon had a greater impact on increasing shoot dry weight compared to root dry weight, with shoot weight being several times higher than root weight.



(a) **(b)**

Fig. 3. Shoot and root dry weight plant^{-1} of pot grown sunflower as affected by salinity (a) and silicon (b). Here, S_0 and S_8 indicate salinity while Si_0, Si_1, Si_2, and Si_3 indicate 0, 0.3, 0.6, and 0.9 mM silicon foliar spray. Different letters indicate the means are statistically different (a) between salinity; (b) among silicon. Vertical bars indicate ±SE.

4.5 Yield attributes and seed yield

Head circumference, head diameter, seed number head^{-1}, 1000 seed weight, and seed yield plant^{-1} were reduced significantly due to salinity (8 dS m^{-1}) (Table 4).In control (non-saline) sunflower plants, head circumference and head diameter measured 63.8 cm and 20.3 cm, respectively. However, salinity stress reduced these values by 21% and 10%. Similarly, seed number head^{-1} decreased by 7%, from 668 in control plants to a lower value under saline conditions. The relatively smaller reduction in seed number head^{-1} compared to other parameters may be attributed to a decrease in seed size rather than seed count. Additionally, the 1000-seed weight in control plants was 42.4 g but declined by 16% under saline conditions. Non-saline plants also produced a higher seed yield (27.4 g), while salinity significantly ($p<0.01$) reduced seed yield per plant by 22% compared to the control (Table 4).

Silicon application positively influenced sunflower growth and yield components (Table 5). Under non-saline conditions, increasing silicon levels progressively improved head circumference, head diameter, seed number per head, 1000-seed weight, and overall seed yield per plant. The highest improvements were observed with 0.9 mM Si foliar spray, where head circumference and head diameter increased by 23% and 36%, respectively. Seed number head^{-1} rose by 6%, while the 1000-seed weight improved by 10% compared to the non-saline control. The seed yield per plant increased by 25%, demonstrating that silicon plays a beneficial role in enhancing yield attributes under non-stressed conditions.

A significant interaction between salinity and silicon was observed in head circumference and head diameter in pot-grown sunflowers (Table 6). The largest head circumference and head diameter were recorded in plants treated with 0.9 mM silicon under non-saline conditions (S_0Si_3), whereas the smallest values were observed in saline treatment under zero Si foliar spray.

Table 4. Yield attributes and seed yield of sunflower as affected by salinity

	Yield and Yield Attributes				
Treatment Salinity (dS m^{-1})	Head circumference (cm)	Head diameter (cm)	Seed number head^{-1}	1000 Seed weight (g)	Seed yield plant^{-1} (g)
0	63.8 a	20.3 a	667.9 a	42.4 a	27.4 a
8	50.2 b	18.2 b	620.8 b	35.5 b	21.4 b
CV (%)	2.94	6.01	6.4	6.5	7.9
P value	<0.01	<0.01	<0.01	<0.01	<0.01
SE (±)	0.69	0.47	8.8	0.79	0.78

Different letters in a column indicate the means are statistically different according to Duncan's Multiple Range Test ($p \leq 0.05$). Here, CV = Coefficient of variation, SE= Standard Error.

Table 5. Seed yield of sunflower as affected by foliar application of silicon

Treatment Salinity ($dS\ m^{-1}$)	Yield and yield attributes				
	Head circumference (cm)	Head diameter (cm)	Seed number $head^{-1}$	1000 Seed weight (g)	Seed yield $plant^{-1}$ (g)
0	50. 5 d	16.9 c	626.0 c	36.8 b	21.5 c
0.1	55.3 c	17.2 c	635.6 bc	38.5 ab	24.3 b
0.2	59.7 b	19.9 b	660.2 ab	39.8 a	25.2 ab
0.3	62.4 a	23.0 a	665.7 a	40.5 a	26.8 a
CV (%)	2.94	6.01	6.4	6.5	7.9
P value	<0.01	<0.01	<0.01	<0.05	<0.01
SE (±)	0.97	0.67	12.5	1.13	1.1

Different letters in a column indicate the means are statistically different according to Duncan's Multiple Range Test ($p \leq 0.05$). Here, CV = Coefficient of variation, SE= Standard Error.

Table 6. Head circumference and head diameter of sunflower as affected by the interaction of Silicon and salinity

Salinity x Si	Head circumference (cm)	Head diameter (cm)
$S_0 Si_0$	57.5 c	16.7 c
$S_0 Si_1$	63.6 b	17.8 c
$S_0 Si_2$	65.7 ab	22.0 b
$S_0 Si_3$	68.2 a	24.5 a
$S_8 Si_0$	43.5 e	17.6 c
S_8Si_1	46.9 e	15.9 c
S_8Si_2	53.7 d	17.8 c
S_8Si_3	56.6 c	21.5 b
CV (%)	2.94	6.01
P value	<0.05	<0.05
SE (±)	1.37	0.94

Different letters in a column indicate the means are statistically different. Here, S_0 and S_8 indicate salinity while Si_0, Si_1, Si_2, and Si_3 indicate 0, 0.3, 0.6, and 0.9 mM silicon foliar spray.

4.6 Ion uptake (Na, K and Si)

Salinity significantly increased Na uptake (0.8%) and decreased K (0.4%) and Si uptake (1.7%) which represent increase in 15% Na and decrease in K 10% and Si 24% compared to that of respective control values (Table 6).

Sodium uptake significantly decreased and K and Si uptake increased gradually with the increase in Si application (Table 7). Under control (zero Si) the sodium concentration was 6.0 which was decreased 18%, 20% and 28% due to application of 0.3, 0.6, and 0.9 mM Si application, respectively, while the K uptake was increased 9%, 12% and 24% and Si uptake was increased 29%, 51% and 71%, respectively, due to Si application.

The interaction effect of salinity and Si was found significant in ion accumulation of pot grown sunflower (Table 8). With the increase in Si under both non-saline and saline condition, sodium (Na) uptake decreased and Si uptake increased. The highest sodium (Na) uptake due to interaction was found in saline treatment under zero silicon (S_8 Si_0), while the lowest was in zero salinity and 0.9 mM Si foliar spray. Conversely, the highest Si uptake was found in zero salinity and 0.9 mM Si foliar spray treatment and lowest in saline treatment under zero silicon. Under non-saline conditions, potassium (K) uptake increased with higher Si levels, although the lowest K uptake was found in the saline treatment with 0.6 mM of Si foliar spray.

Table 7. Ion accumulation in shoot of sunflower as affected by salinity

Salinity (dS m^{-1})	Na (%)	K (%)	Si (%)
0	4.6 b	3.9 a	7.0 a
8	5.4 a	3.5 b	5.3 b
CV (%)	6.6	7	6.1
P value	<0.01	<0.01	<0.01
SE (±)	0.11	0.10	0.12

Different letters in a column indicate the means are statistically different according to Duncan's Multiple Range Test ($p \leq 0.05$). Here, CV = Coefficient of variation, SE= Standard Error.

Table 8. Ion accumulation in shoot of sunflower as affected by foliar applied silicon

Silicon (m M)	Na (%)	K (%)	Si (%
0	6.0 a	3.3 c	4.5 d
0.3	4.9 b	3.6 bc	5.8 c
0.6	4.8 b	3.7 b	6.8 b
0.9	4.3 c	4.1 a	7.7 a
CV (%)	6.6	7	6.1
P value	<0.01	<0.01	<0.01
SE (±)	0.16	0.14	0.18

Different letters in a column indicate the means are statistically different according to Duncan's Multiple Range Test ($p \leq 0.05$). Here, CV = Coefficient of variation, SE= Standard Error.

Table 9. Ion accumulation in shoot of sunflower as affected by the interaction of silicon and salinity

Salinity x Si	Na (%)	K (%)	Si (%)
S_0 Si_0	5.5 b	3.1 d	5.2 d
S_0 Si_1	4.5 d	3.6 bc	6.4 c
S_0 Si_2	4.8 d	4.3 a	7.5 d
S_0 Si_3	3.7 e	4.4 a	9.1 a
S_8 Si_0	6.5 a	3.5 bcd	3.8 e
S_8Si_1	5.2 bc	3.5 bcd	5.2 d
S_8Si_2	5.1 c	3.2 cd	6.1 c
S_8Si_3	4.9 cd	3.8 d	6.3 c
CV (%)	6.6	7.1	6.0
P value	<0.05	<0.01	<0.01
SE (±)	0.22	0.21	0.25

Different letters in a column indicate the means are statistically different. Here, S_0 and S_8 indicate salinity while Si_0, Si_1, Si_2, and Si_3 indicate 0, 0.3, 0.6, and 0.9 mM silicon foliar spray.

CHAPTER V
DISCUSSION

Silicon (Si), an essential metalloid, mitigates several abiotic stresses, including salinity, drought, and heavy metal toxicity (Liang et al., 2007; Epstein et al., 1999). In the present study, salinity caused significant reductions in plant growth, dry weight, seed yield, and yield attributes. However, applying Si effectively alleviated salinity stress by improving these parameters (Kabir et al., 2024). Notably, the decrease in plant height due to salinity was reversed following Si application, likely due to its ability to promote cell division and elongation (Liang et al., 2015). Similarly, plant height was reduced under saline conditions (Fig. 1a), whereas silicon application led to an increase in plant height (Fig. 1b).

A study on the effects of Si in improving growth under salt-stressed conditions in soybean highlighted that Si alleviated NaCl stress by enhancing gibberellin levels and reducing abscisic acid (ABA) and proline concentrations (Lee et al., 2010). Chlorophyll content increased with higher silicon level (Table 2) but decreased under saline conditions (Table 1). Similarly, chlorophyll content and overall plant growth were enhanced by foliar spraying with potassium silicate (Wang and Galletta, 1998). Under 150 mM sodium chloride stress, Si improved shoot growth, chlorophyll content, and membrane permeability by enhancing water content and maintaining ion balance in the shoots (Tahir et al., 2012). Enhanced photosynthesis and water use efficiency, resulting from reduced oxidative damage to the photosynthetic apparatus, were also observed in alfalfa following Si application (Liang, 1998). However, Under 150 mM NaCl stress, no significant effects were observed on chlorophyll a, chlorophyll b, their ratio (a/b), relative water content (RWC), relative membrane permeability (RMP), or Cl^-, K^+, and P contents in leaves and roots. However, salt stress significantly increased the C_i/C_a ratio, free proline levels, and Na^+ concentrations in both leaves and roots across all sunflower cultivars. However, Salt stress (150 mM NaCl) had minimal impact on chlorophyll content, RWC, RMP, and certain nutrient levels but significantly increased proline and Na^+ concentrations in sunflower cultivars (Shahbaz et al.,2011).

The role of Si in cell elongation, division processes, and hormone balance has been documented (Elawad et al., 1982a, b; Abdalla, 2011; Taher et al., 2018). The Moulata and

BRRI dhan77 varieties displayed the greatest Si responsiveness, with Moulata exhibiting remarkable increases in shoot dry weight, root volume, leaf number, and Si uptake (Haque, Hoque et al., 2023). Interestingly, leaf number was relatively stable during the cooler temperatures of January but significantly increased as temperatures rose in February, indicating temperature-driven growth (Kabir et al., 2024). However, Si application likely increased leaf number, as indicated by the enhanced shoot biomass (Fig. 3b).

Reductions in plant biomass serve as reliable indicators of salinity stress (Munns, 2011). In sorghum and sunflower, Si application increased shoot biomass by enhancing net photosynthesis under salt stress (Kabir et al., 2024; Yin et al., 2013; Hurtado et al., 2020). However, the addition of Si to the growth medium consistently reduced photosynthetic pigment content but enhanced root and shoot dry matter production in sunflower (Calero Hurtado et al., 2024). Although studies on the effects of Si on sunflower biomass and yield are limited (Boldt et al., 2018), the beneficial effects of Si on root morphology in seedlings and mature plants, leading to increased root dry weight, are well established (Liu et al., 2018). However, Si application improved root dry weight (Fig. 3b) as well as increased in control (zero salinity) condition (Fig.3a).

In a study on sunflowers grown in a soilless peat-based substrate, the application of silicon (Si) increased the Si concentration from 4.9 to 15.3 g kg^{-1}, as reported by Kamenidou et al. (2008). Similarly, Si percentage increased with the application of Si (Table 7).In the current study, the Si concentration in sunflower shoots, which include both stems and leaves, ranged from 9.3 to 11.3 g kg^{-1} dry weight. These findings align with the results of Kamenidou et al. (2008), confirming the consistency of Si accumulation in sunflower shoots under similar conditions.

The accumulation of toxic sodium (Na^+) in the protoplasm leads to ionic imbalances, causing various metabolic and nutritional disorders that ultimately reduce plant growth (Munns, 2011). High levels of Na^+ in the soil also reduce potassium (K^+) concentrations in plants, particularly in the roots, exacerbating the stress effects (Agrie et al., 1998). In contrast, foliar application of Si proved to be more effective than soil additives or combined methods in increasing the K^+ concentration and K^+/Na^+ ratio, significantly reducing Na^+ and chloride (Cl^-) levels in salt-stressed sweet basil (Farouk et al., 2020). These results underscore the potential of Si applications, particularly foliar spraying, to enhance ionic homeostasis and mitigate plant salinity stress. Similarly, foliar application of silicon reduced sodium levels while increasing potassium and silicon concentrations under non-saline condition (Table 7).The observed reductions in Na^+ uptake and enhanced K^+ uptake due to Si are consistent with findings in wheat (Ali et al., 2009), rice (Alsaeedi et al., 2018), and cucumber (Gurmani et al., 2013). Si mitigates salinity by reducing plasma membrane permeability and maintaining membrane integrity (Zhu et al., 2004). Additionally, the availability of K^+ is essential for cell enlargement, osmotic regulation, and overall plant homeostasis (Coskun et al., 2016). Exogenous Si application enhances the uptake and selective translocation of K^+, maintaining ionic homeostasis by protecting the proton pump activities in root tip membranes (Xu et al., 2015; Liang et al., 2006). However, Na uptake increased with increasing salinity but decreased K and Si (Table 6).

Foliar applications of silicic acid significantly boost grain and straw yields compared to control in wetland rice (Prakash et al., 2011) and maize (Haque, Mobaswera et al., 2023). In sweet peppers, Si application under salt stress decreased fruit yield, fresh fruit weight, and the number of fruits per plant (Abdelaal et al., 2020). For rice, Si application significantly improved the number of panicles, filled grains per panicle, 1000-grain weight, and grain yield per pot (Akter et al., 2017). Similarly, silicon application enhanced seed number head^{-1}, 1000 seed weight and yield (Table 5), although these parameters declined under saline conditions (Table 4). Under non-saline conditions, increasing silicon levels gradually enhanced head circumference and diameter, with the highest improvements of 23% and 36%, respectively, observed at 0.9 mM Si foliar spray (Table 5).Silicon supplementation in the growth medium of plants exposed to saline and/or sodic water significantly increased sunflower head diameter by 22–30% (Hussain et al., 2018), showing a similar trend with the highest HD of 18.77 cm under full irrigation and the lowest at 16.82 cm under limited irrigation, while the decline in seed yield with reduced irrigation was associated with the corresponding decrease in HD (Ali et al., 2024).

The study demonstrated a significant interaction between salinity and silicon on SPAD values (Table 3) and ion accumulation in sunflower shoots (Table 8). Similarly, Kabir et al. (2024) reported that salinity and silicon interactions had a notable impact on seed weight per plant.

While sunflowers are generally considered intermediate Si accumulators, they have shown positive responses in various parameters when Si is applied, both under salt stress and non-stress conditions. Therefore, to expand sunflower cultivation and enhance seed yield, applying Si alongside other fertilizers during sowing could be advantageous. More pot trials using over 0.9 mM Si spray should be conducted, and field trials with sunflowers and other crops should also be carried out simultaneously with Si.

CHAPTER VI

SUMMARY, CONCLUSION AND FUTURE RESEARCH

Summary

The pot experiment was carried out at the research field Professor Dr. Purnendu Gain's field Laboratory at Khulna University during the winter season of 2023-24, from November to March. The study was aimed to determine the alleviating effects of salinity by foliar spray of silicon (Si) on the sunflower to modulate the biomass yield and ion (Na, K, and Si) accumulation under saline conditions. The experiment involved two salinity levels (0 and 8 dS m^{-1}) and four Si levels (0, 0.3, 0.6, and 0.9 mM foliar spray). The experiment was laid out in two factors completely randomized design (CRD) with three replications. This study examined how the application of silicon (Si) affects sunflower plants grown in saline soil conditions through a pot experiment, concentrating on plant growth, yield attributes, and ion uptake. The results showed that salinity had adverse effects on plant height, leaf area, Chlorophyll content index (SPAD value), shoot and root dry weight, and yield attributes such as head circumference, head diameter, seed number $head^{-1}$, 1000 seed weight, and seed yield. However, the application of silicon (Si) mitigated these detrimental effects of salinity on the measured parameters. Field data was collected at different DAS. During the initial growth stages, salinity had no impact on plant height. However, at 48, 64, and 80 days after sowing (DAS), plant height was reduced by 10%, 9%, and 6%, respectively. Silicon application significantly influenced plant height at 32 DAS, 48 DAS, 64 DAS, and 80 DAS (Fig.1.b), with the highest (109.9 cm) was found in 0.9 mM Si foliar spray. Salinity-related height changes varied across growth phases. The increase in leaf number per plant was likely due to the application of silicon rather than the effects of salinity. Both salinity and silicon application did not significantly affect leaf number at 32 DAS, but they showed variation in leaf number at subsequent growth stages. Numerically, the results revealed that at 80 DAS, the maximum leaf number was observed in the 0.9 mM Si foliar spray under non-saline condition. At 50 DAS, the highest SPAD value (CCI) was recorded with 0.9 mM Si, but it decreased with higher Si levels, likely due to the white silicon powder on the leaves, which contributed to a reduction in chlorophyll content. The interaction of salinity and Si was significant in leaf chlorophyll content index at 50 DAS. Under salinity conditions, a notable decrease of 18% in shoot dry weight and 19% in root dry weight was observed. In contrast, the application of silicon significantly increased both shoot and root dry weight, with the highest values recorded at 0.9 g Si mM foliar spray.

Salinity caused a significant reduction in head circumference (21%), head diameter (10%), seed number head^{-1} (7%) and 1000 grain weight (16%). Seed yield decreased by 22% compared to the control. Si application at 0.9 mM Si foliar spray increased head circumference (23%), head diameter (36%), seed number head^{-1} (8%), 1000 seed weight (10 %), and seed yield (25%), compared to that of control (zero salinity with zero silicon). The interaction of salinity and Si was significant in head circumference and head diameter of pot grown sunflower. Salinity reduced sodium (Na) uptake by 55%, potassium (K) uptake by 25%, and silicon (Si) uptake by 37%. However, these effects were reversed when silicon was applied, increasing both potassium and silicon uptake while decreasing sodium uptake. The interaction of salinity and Si was significant in Ion accumulation in shoot of pot grown sunflower. According to this, silicon might support the plant's ion balance maintenance. Based on the results of the experiments, it can be said that 0.9 mM Si foliar spray performed better compared to other treatments under non saline condition.

Conclusion

The study showed that salinity depressed growth and yield attributes, and yield of sunflower, but this depressing effect was improved with the application of Si. Salinity positively increased biomass, yield attributes, and seed yield even at even non-saline level. A possible synergistic effect was found from the interaction of salinity and Si that suppress the negative effect of salinity. Based on these findings, Si application by foliar spraying to saline soil may be one of the efficient ways to improve sunflower yield under saline conditions.

Future Research

As the current research is conducted in pot, if Si decreases salinity effect and increases growth and seed yield. Further research is needed to confirm the results and determine the alleviating effects of salinity by foliar spray of silicon. More pot trials including more amount of Si than 0.9 mM Si foliar spray should be done and field trials of sunflower and other crops also need to be done simultaneously with Si in the salt-affected coastal area of Bangladesh.

CHAPTER VII

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