Silicon exhibits dose-dependent impact on barley growth

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Abstract. As population growth accelerates, agriculture's significance in our lives remains paramount. However, this surge in population has led to land degradation and increased food scarcity. The importance of silicon (Si) on plants has garnered significant attention in agricultural research. This study was aimed at examining the impact of Si on barley (Hordeum vulgare) plants by administering varying concentrations (5µM, 10µM, 20µM, 50µM, 100µM, 200µM, 500µM, 1000µM) and assessing their effects on plant growth parameters, particularly root and shoot lengths, and root fresh weight. Our study employed a controlled experimental setup to observe how barley plants respond to varying concentrations of Si. The data indicates that Si concentrations up to 10µM offer advantageous effects on barley compared to the control group, suggesting its potential in bolstering agricultural productivity. Similarly, concentrations of 20µM, 50µM, and 100µM were identified as safe for plant growth, opening avenues for their agricultural utilization. However, concentrations of 500µM and 1000µM resulted in complete inhibition of plant growth, emphasizing the necessity for cautious Si application in agriculture to prevent adverse impacts on crop yields. These findings underscore the importance of fine-tuning Si concentrations in agricultural practices to optimize benefits while mitigating potential risks to plants.

Keywords: Silicon, shoot, root, concentration, growth, biomass

1 Introduction

Ensuring a sustainable agricultural capacity capable of consistently fulfilling the dietary and resource needs of a growing global population is of paramount importance for human survival and all related endeavors [1]. Moreover, the demand for food and nutrition is escalating at a pace surpassing population growth rates, presenting a formidable challenge in meeting global food security requirements [2]. The Green Revolution emerged as a response to this imperative, particularly benefiting developing nations like India by effectively combating starvation through increased agricultural output. This was achieved through the adoption of high-yielding seed varieties, improved farm machinery, and a significant boost in chemical fertilizer usage [3]. However, while these practices have facilitated the growth and sustainability of food production, they have also had notable impacts on human health and the environment. Plants thrive in dynamic environments where they often encounter challenges that hinder their growth and development [4]. These challenges include both biotic stresses like pathogen attacks and herbivore damage, as well as abiotic stresses such as nutrient deficiencies, extreme temperatures, drought, and high levels of salt and toxic metals like cadmium, arsenic, and aluminum in the soil [5]. Since the availability of nutrients significantly impacts crop productivity, it becomes imperative to comprehend the mechanisms of nutrient transport, uptake, assimilation, and their biological interactions to improve plant growth and development. To address the rising demand for food amidst these challenges, various solutions are being implemented, including the utilization of silicon (Si). Therefore, an effective solution for increasing good production is the dire need of the hour.

Numerous studies conducted in the early 20th century have suggested that Si exerts a positive impact on plant growth and is considered a valuable supplement [6]. While Si is typically deemed non-essential or quasi-essential [7] for plant growth and development [8], it ranks as the second most abundant element in the Earth's crust after oxygen [9]. Plants absorb Si primarily in the form of silicic acid, Si(OH)₄ [10]. In recent studies, it has been demonstrated that Si boosts primary metabolism by enhancing photosynthesis [11] and nutrient absorption [12]. Additionally, it stimulates secondary metabolism by promoting the synthesis of phenolic compounds, which serve either as antioxidants (such as flavonoids) or contribute structurally (e.g., lignin) [13]. Consequently, Si has been noted to improve the metabolism of antioxidant or structural phenols in plants facing challenging environmental conditions. The application of Si has been shown to ameliorate the detrimental effects of various abiotic stresses, including drought, salinity, UV-B radiation, temperature extremes, and heavy metals [14], as well as biotic stresses such as pests and diseases [15]. Beyond stress alleviation, Si
interacts extensively with plant organs and tissues, deploying mechanisms to mitigate the adverse effects of potentially harmful foreign particles within plant cells [16].

Barley (*Hordeum vulgare*) ranks as the fourth most produced cereal worldwide, following maize, rice, and wheat [17]. It is grown worldwide in various agricultural systems, ranging from high-input to low-input methods, across diverse environments. It serves as a crucial source of feed and forage for livestock, as well as food and beverages for humans [18]. Therefore, it would be interesting to analyse the interaction of Si with barley plant system. Hence, in this study, we have elucidated the impact of different concentrations of Si on growth of barley seedlings.

2. Material and Methods

The following section details the materials, experimental techniques, and methodologies employed in the investigation. An experiment was conducted to assess the positive effects of Si on plants.

2.1 Plant growth conditions

The barley seeds utilized in this research were sourced from the Indian Agriculture Research Institute (IARI) in New Delhi, India. To ensure viability, the seeds were immersed in a 10% (v/v) sodium hypochlorite solution for 10 minutes as part of the soaking process. Following three to four thorough rinses, they were then submerged in distilled water for an additional two to three hours. By the third day, the seedlings were ready to be transplanted into cups. For this purpose, solutions containing Si (sodium metasilicate) + Hoagland solution (MgSO$_4$.7H$_2$O, Ca(NO$_3$)$_2$.2H$_2$O, Fe+EDTA, KH$_2$PO$_4$, CuSO$_4$.5H$_2$O, KNO$_3$, ZnSO$_4$.7H$_2$O, H$_2$BO$_3$, MnCl$_2$.4H$_2$O, Na$_2$MoO$_4$.2H$_2$O) [19] were used as a growth medium to cultivate barley seedlings at different Si concentrations (5µM, 10µM, 20µM, 50µM, 100µM, 200µM, 500µM, 1000µM).

2.2 Root and shoot length evaluation

After seven days of treatment, the root length and shoot length was manually measured using a measuring scale.

2.3 Fresh/Dry weight evaluation

The barley seedlings were separated into its root and shoot components, and the weights of both were measured using a digital balance. This process was conducted to ascertain the fresh/dry weight of the roots-shoots.

2.4 Statistical Analysis

The statistical analysis involved employing one-way analysis of variance (ANOVA) using SPSS 16.0 software, following confirmation of the data's normal distribution. Duncan’s multiple range test (DMRT) was utilized at a significance level of P<0.05 to discern differences among treatments. The reported values represent the means obtained from three independent biological replicates (n=3).

3. Results and Discussion

During the plant's harvest stage, plant growth parameters were evaluated. Various parameters, including root-shoot length, root/shoot fresh weight, and root/shoot dry weight, were assessed from the experiment. Morphological impact of the treatments is indicated in Fig 1.

Fig. 1. Morphological impact of root and shoot length of barley at different concentration of Si

3.1 Root length (cm/seedling)

Barley root length displayed diverse changes across different Si concentrations, with increases of 14.61%, 20.04%, 12.63%, 6.99%, 5.63%, and 1.77% observed at Si concentrations of 5µM, 10µM, 20µM, 50µM, 100µM, and 200µM respectively, compared to the control group. Conversely, reductions of 6.5% and 16.70% were noted at Si concentrations of 500µM and 1000µM respectively (Fig 2). These results indicate that up to 10µM, there was a modest increase in barley root length. However, beyond this concentration range, decreasing Si levels resulted in a significant reduction in root length, highlighting the importance of optimizing Si concentrations for enhancing barley root growth. These findings suggest that Si has a positive effect on root length, consistent with observations reported by Kuhla et al [20]. This underscores the significance of optimizing the dosage of Si particles to maximize their beneficial impact.

Fig. 2. Graphical representation of root length of barley seedlings treated with different concentration of Si. T1 (control, 0µM Si), T2 (5µM Si), T3 (10µM Si), T4 (20µM Si),
3.2 Root fresh weight (gm/seedling)

The fresh weight of barley roots displayed varying trends, with increases of 9.91%, 16.62%, 7.23%, 5.09%, and 0.26% observed at Si concentrations of 5µM, 10µM, 20µM, 50µM, and 100µM respectively, compared to the control group (Fig 3). Conversely, reductions of 6.16%, 6.70%, and 18.76% were noted at Si concentrations of 200µM, 500µM, and 1000µM respectively. These findings suggest that up to 10µM of Si, there was a modest increase in the fresh weight of roots. However, beyond this optimal range, higher Si concentrations resulted in diminishing returns, with significant reductions in root fresh weight observed at concentrations of 200µM and above. These results indicate that Si positively influences the fresh weight of roots, aligning with findings reported by Dresler et al [21]. This emphasizes the importance of optimizing Si particle dosage to enhance its beneficial effects. It underscores the significance of precisely adjusting Si concentrations to achieve the best outcomes in fostering root growth.

Fig. 3. Graphical representation of root fresh weight of barley seedlings treated with different concentration of Si. T1 (control, 0µM Si), T2 (5µM Si), T3 (10µM Si), T4 (20µM Si), T5 (50µM Si), T6 (100µM Si), T7 (200µM Si), T8 (500µM Si) and T9 (1000µM Si)

3.3 Root dry weight (gm/seedling)

Barley root length exhibited diverse changes, with increments of 11.68%, 19.58%, 15.46%, 4.46% and 2.74% observed at Si concentrations of 5µM, 10µM, 20µM, 50µM and 100µM respectively, compared to the control (Fig 4). Conversely, reductions of 2.74%, 5.84% and 10.99% were noted at Si concentrations of 200µM, 500µM and 1000µM respectively. These results suggest that up to 10µM, there was a modest increase in barley root length, but beyond this threshold, decreasing Si levels led to a significant reduction in root length. These results indicate that Si shows a beneficial impact on root dry weight similar to that of observation given by An et al [22]. These finding are suggestive of importance of optimizing the doses of Si, so that a maximum beneficial impact can be induced.

Fig. 4. Graphical representation of root dry weight of barley seedlings treated with different concentration of Si. T1 (control, 0µM Si), T2 (5µM Si), T3 (10µM Si), T4 (20µM Si), T5 (50µM Si), T6 (100µM Si), T7 (200µM Si), T8 (500µM Si) and T9 (1000µM Si)

3.4 Shoot length (cm/seedling)

Barley shoot length exhibited diverse changes, with increments of 13.93%, 19.73%, 13.08%, 11.26%, 6.56%, and 1.78% observed at Si concentrations of 5µM, 10µM, 20µM, 50µM, 100µM, and 200µM respectively, compared to the control (Fig 5). Conversely, reductions of 0.44% and 7.21% were noted at Si concentrations of 500µM and 1000µM respectively. These results suggest that up to 10µM, there was a modest increase in barley shoot length, but beyond this threshold, decreasing Si levels led to a significant reduction in shoot length.

Fig. 5. Graphical representation of shoot length of barley seedlings treated with different concentration of Si. T1 (control, 0µM Si), T2 (5µM Si), T3 (10µM Si), T4 (20µM Si), T5 (50µM Si), T6 (100µM Si), T7 (200µM Si), T8 (500µM Si) and T9 (1000µM Si)

3.5 Shoot fresh weight (gm/seedling)

The fresh weight of barley shoots displayed diverse changes, with increases of 17.92%, 33.06%, 20.48%, 19.25%, 16.67%, 10.50%, and 3.45% observed at Si concentrations of 5µM, 10µM, 20µM, 50µM, 100µM, 200µM, and 500µM respectively, compared to the control group. Conversely, a reduction of 5.51% was noted at a Si concentration of 1000µM (Fig 6). These findings suggest that up to 10µM, there was a modest increase in shoot fresh weight, but beyond this threshold, decreasing Si levels led to a significant reduction in shoot fresh weight. These findings suggest that Si exerts a positive influence on the fresh weight of shoot,
consistent with observations documented by Karmollachaab et al [23]. This underscores the criticality of fine-tuning Si particle dosage to augment its advantageous effects. It highlights the importance of accurately adjusting Si concentrations to optimize outcomes in promoting root growth.

Fig. 6. Graphical representation of shoot fresh weight of barley seedlings treated with different concentration of Si. T1 (control, 0µM Si), T2 (5µM Si), T3 (10µM Si), T4 (20µM Si), T5 (50µM Si), T6 (100µM Si), T7 (200µM Si), T8 (500µM Si) and T9 (1000µM Si)

3.6 Shoot dry weight (gm/seedling)

The study found that barley shoot dry weight exhibited diverse changes across different Si concentrations. Increases of 18.66%, 25.33%, 16%, 12%, 5.33%, and 1.33% were observed at Si concentrations of 5µM, 10µM, 20µM, 50µM, 100µM, and 200µM respectively, compared to the control group (Fig 7). Conversely, reductions of 4% and 8% were noted at Si concentrations of 500µM and 1000µM respectively. These results indicate that up to a Si concentration of 10µM, there was a modest increase in barley shoot dry weight. However, beyond this threshold, decreasing Si levels led to a significant reduction in dry weight. This suggests that there is an optimal range of Si concentration that promotes barley shoot dry weight, and deviations from this range can adversely affect plant growth. These results indicate that Si positively impacts shoot dry weight, in line with findings reported by Fiala et al [24]. This emphasizes the necessity of precisely adjusting Si particle dosage to enhance its beneficial effects. It underscores the significance of optimizing Si concentrations to achieve optimal outcomes in promoting root growth. Therefore, further research is needed to determine the most effective Si dosage for maximizing its beneficial impact on overall plant development.

Fig. 7. Graphical representation of shoot dry weight of barley seedlings treated with different concentration of Si. T1 (control, 0µM Si), T2 (5µM Si), T3 (10µM Si), T4 (20µM Si), T5 (50µM Si), T6 (100µM Si), T7 (200µM Si), T8 (500µM Si) and T9 (100 µM Si)

4 Conclusion

The data suggests that Si concentrations up to 10µM demonstrate advantageous effects on barley, surpassing those of the control group. Likewise, concentrations of 20µM, 50µM, and 100µM were deemed benign to plant growth. However, higher concentrations of 500µM and 1000µM led to a complete cessation in plant growth and detrimentally impacted their development. These results underscore the potential of Si application in agriculture, highlighting its role in promoting plant growth and productivity. It emphasizes the importance of carefully regulating Si concentrations to optimize agricultural practices and ensure sustainable crop yield. Overall, the correct concentration of Si application in agriculture can significantly benefit crop production by improving disease resistance, abiotic stress tolerance, nutrient uptake, photosynthetic efficiency, and reducing pesticide dependency. Further research in this area could offer valuable insights for enhancing agricultural productivity while mitigating potential adverse effects on plant growth.

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