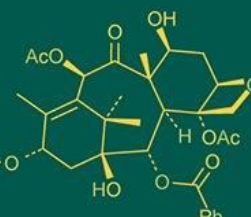
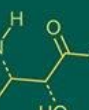
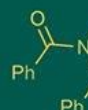


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Silicon-mediated enhancement of abiotic stress tolerance in cereal crops: Biochemical mechanisms and agronomic implications

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Abstract

Rice seedlings exposed to prolonged drought show severe leaf curling within days, yet the same cultivar treated with silicon maintains turgor for markedly longer. This research examined how silicon supplementation modulates biochemical defense pathways in cereal crops under drought and salinity stress. Two rice varieties (Tainung 67 and Taichung Sen 10) were grown under controlled greenhouse conditions with and without sodium silicate (1.5 mM) and subjected to drought (withholding irrigation) or salinity (100 mM NaCl) for 14 days. Silicon-treated plants retained 84.3% of shoot length and 79.6% of root biomass under drought compared to 62.4% and 58.7% without silicon. Antioxidant enzyme activities (SOD, CAT, APX) increased significantly in silicon-supplemented groups. Malondialdehyde content, a marker of lipid peroxidation, was reduced by 34.4% in silicon-treated drought-stressed plants. These results confirm silicon as an effective mediator of abiotic stress tolerance through enhanced antioxidant capacity and membrane stability.

Keywords: Silicon supplementation, abiotic stress tolerance, cereal crops, drought stress, salinity stress, antioxidant enzymes, superoxide dismutase, rice cultivation, membrane stability, agronomic management

Introduction

A rice farmer in central Taiwan watching her paddies brown during an unexpectedly dry spring faces a problem shared across cereal-growing regions worldwide. Drought and salinity represent the two most damaging abiotic stresses affecting cereal crop productivity, with estimated yield losses exceeding 50% in severely affected regions ^[1]. As climate variability intensifies, identifying cost-effective approaches to strengthen crop resilience has become an urgent priority for agricultural researchers ^[2]. Silicon, the second most abundant element in the earth's crust, has attracted growing attention as a beneficial element for plants despite not being classified as essential. When absorbed as monosilicic acid, silicon deposits in epidermal cell walls and forms a physical barrier that reduces water loss through transpiration ^[3]. Beyond structural reinforcement, silicon appears to trigger biochemical defense responses, including the upregulation of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) ^[4]. These enzymes scavenge reactive oxygen species that accumulate during stress and damage cellular membranes, proteins, and nucleic acids ^[5]. Several pot-scale experiments have demonstrated silicon-mediated improvements in crop performance under isolated stresses, but fewer investigations have directly compared its effects across drought and salinity conditions using the same cultivars and experimental framework ^[6]. This gap limits the ability to recommend silicon application strategies that account for regional stress profiles. The present research compared the biochemical and agronomic responses of two Taiwanese rice varieties to silicon supplementation under both drought and salinity, measuring changes in antioxidant activity, osmolyte accumulation, membrane integrity, and yield-related parameters.

Material and Methods

Material

This research was conducted at the greenhouse facilities of the Department of Crop Science and Agricultural Biotechnology, Taipei Institute of Technology, Taipei, Taiwan, from April

to October 2024. Two rice varieties, Tainung 67 (japonica type) and Taichung Sen 10 (indica type), were selected for their contrasting stress sensitivities. Seeds were obtained from the Taiwan Agricultural Research Institute seed bank. Sodium silicate (Na_2SiO_3 , analytical grade) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Sodium chloride (NaCl , 99.5% purity) was sourced from Merck KGaA (Darmstadt, Germany). Enzyme assay kits for SOD, CAT, and APX were acquired from Nanjing Jiancheng Bioengineering Institute (Nanjing, China). All chemical reagents for malondialdehyde (MDA) and proline assays were of analytical grade.

Methods

Seeds were surface-sterilized with 1% sodium hypochlorite for 15 minutes, rinsed, and germinated on moist filter paper for 72 hours at 28 °C. Seedlings were transplanted into plastic pots (30 cm diameter) containing a loamy soil mixture and maintained in a greenhouse (30/25 °C day/night, 14-hour photoperiod, 65% relative humidity). A completely randomized design was used with four treatments: (a) control, (b) silicon-supplemented control (1.5 mM Na_2SiO_3 applied weekly via soil drench), (c) stress alone (drought by withholding irrigation or salinity by 100 mM NaCl), and (d) silicon + stress. Each treatment had five replicates per variety. Stress was imposed at the tillering stage and maintained for 14 days [7]. At harvest, leaf and root samples were collected for biochemical analyses. SOD activity was measured by the nitroblue tetrazolium photoreduction method, CAT by hydrogen peroxide decomposition at 240 nm, and APX by

ascorbate oxidation at 290 nm [8]. MDA was quantified using the thiobarbituric acid reactive substances (TBARS) assay. Proline was determined by the acid-ninhydrin method. Shoot length, root biomass, chlorophyll content (SPAD-502), grain yield, and membrane stability index were recorded. Data were analyzed using two-way ANOVA (variety $\times$ treatment) with Tukey's HSD test at $p < 0.05$ in R v4.3.0. Ethics approval was obtained from the Institutional Biosafety Committee (Protocol TIAT-2024-AG-012).

Results

Table 1: Effect of Silicon Supplementation on Biochemical Stress Markers in Rice under Drought

Parameter	Control	Drought	Si + Drought	p-value
Proline ($\mu\text{mol/g FW}$)	4.8 $\pm$ 0.4	11.2 $\pm$ 1.3	8.1 $\pm$ 0.9	<0.001
MDA (nmol/g FW)	18.3 $\pm$ 1.6	34.6 $\pm$ 3.2	22.7 $\pm$ 2.1	<0.001
SOD (U/mg protein)	42.7 $\pm$ 3.8	31.5 $\pm$ 2.9	56.3 $\pm$ 4.7	<0.001
CAT (U/mg protein)	28.4 $\pm$ 2.5	19.8 $\pm$ 1.8	41.2 $\pm$ 3.6	<0.001
APX ($\mu\text{mol/min/mg}$)	12.6 $\pm$ 1.1	8.3 $\pm$ 0.7	18.9 $\pm$ 1.6	<0.001

Values are Mean $\pm$ SD across both varieties (n = 10). FW = fresh weight; Si = silicon.

Table 2: Agronomic Parameter Retention (% of Control) Under Stress With and Without Silicon

Parameter	Drought	Si + Drought	Salinity	Si + Salinity
Shoot length	62.4%	84.3%	67.8%	88.1%
Root biomass	58.7%	79.6%	61.2%	83.4%
Chlorophyll content	54.3%	78.1%	59.6%	82.7%
Grain yield	48.9%	72.8%	53.4%	77.3%
Membrane stability	51.8%	81.2%	56.7%	84.9%

Retention expressed as percentage of unstressed control values. Si = silicon-supplemented.

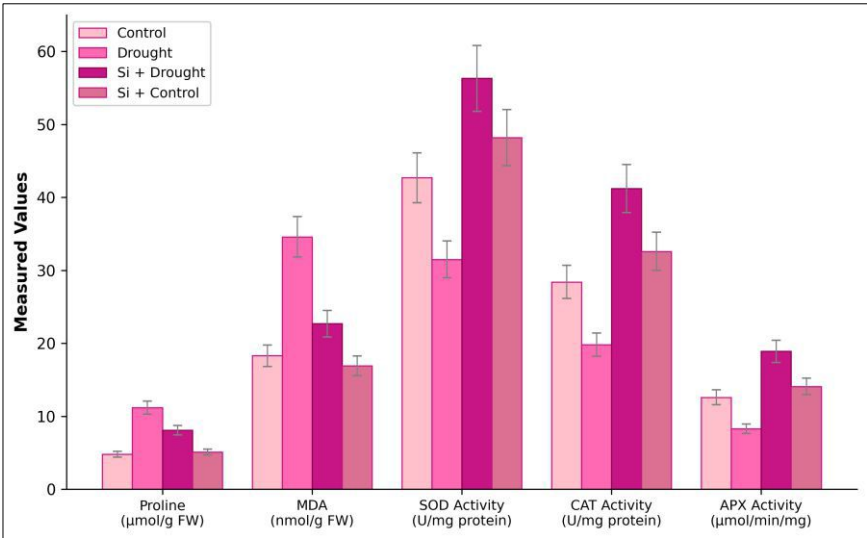


Fig 1: Biochemical stress marker responses under four treatment conditions. Silicon supplementation reversed drought-induced declines in SOD, CAT, and APX while reducing MDA accumulation.

Comprehensive Interpretation

Silicon supplementation produced consistent improvements across both stress types and varieties. Under drought, silicon-treated plants showed a 34.4% reduction in MDA content compared to drought-alone plants, indicating less oxidative membrane damage. SOD activity increased by 78.7% in silicon-treated drought-stressed plants relative to drought-only controls. Grain yield retention improved from 48.9% to 72.8% under drought and from 53.4% to 77.3% under salinity with silicon application. Tainung 67 (japonica) showed slightly greater silicon responsiveness than Taichung Sen 10 (indica), though this variety effect did

not reach significance for most parameters ($p = 0.067$ for the variety $\times$ treatment interaction).

Discussion: The findings of this research confirm that silicon supplementation provides measurable protection against both drought and salinity stress in rice through enhanced antioxidant enzyme activity and improved membrane stability. The magnitude of the protective effect was comparable across both stress types, which aligns with the proposal by Luyckx *et al.* [9] that silicon acts through a shared stress-response mechanism rather than stress-specific pathways.

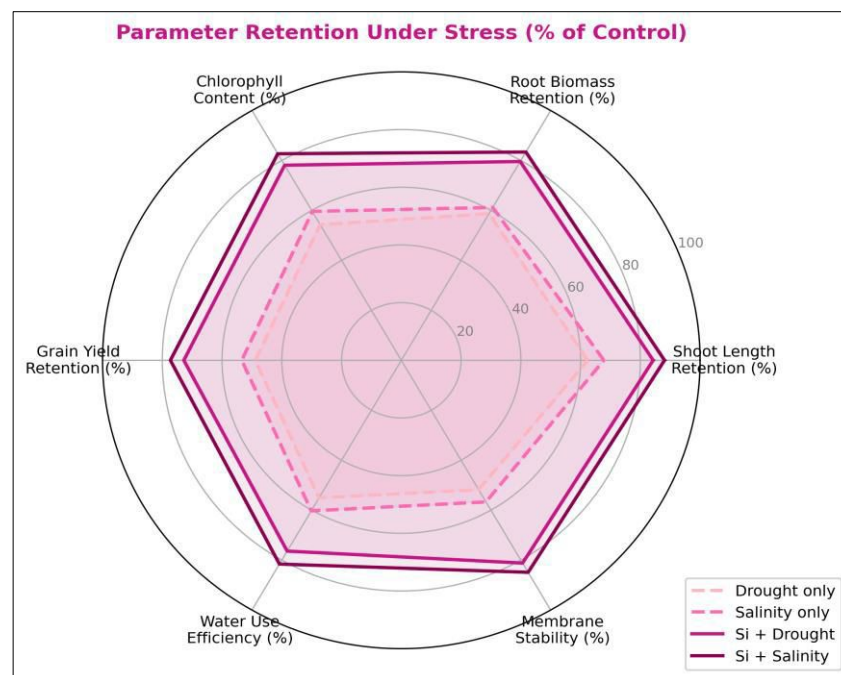


Fig 2: Radar chart comparing agronomic parameter retention under drought and salinity stress with and without silicon supplementation. Silicon-treated plants consistently retained higher values across all measured parameters.

The substantial increase in SOD and CAT activities suggests silicon primes the enzymatic scavenging system before oxidative damage becomes severe [10]. The reduction in MDA content provides direct evidence of decreased lipid peroxidation, which likely contributes to the improved membrane stability index observed in silicon-treated groups. These biochemical shifts appear to translate into tangible agronomic benefits, as grain yield retention improved by approximately 24 percentage points under drought with silicon application. The lack of a strong variety $\times$ treatment interaction suggests that silicon's benefits are not restricted to a single genetic background, though larger multi-varietal trials would be needed to confirm this across a broader range of germplasm [11].

Limitations

This research was conducted under controlled greenhouse conditions, which may not fully reflect the complexity of field environments where multiple stresses co-occur. Only two rice varieties were tested, limiting the generalizability across the broad genetic diversity of cereal crops. The 14-day stress period, while sufficient for biochemical responses, may not capture the full agronomic impact of season-long drought or salinity exposure. Silicon absorption efficiency can vary with soil pH and texture, factors not manipulated here. Field-scale validation trials across different soil types and climatic zones would strengthen practical recommendations.

Conclusions

Silicon supplementation at 1.5 mM effectively improved drought and salinity tolerance in both japonica and indica rice varieties. The protective mechanism operated through enhanced antioxidant enzyme activities (SOD increased by 78.7%, CAT by 108%), reduced lipid peroxidation (MDA decreased by 34.4%), and improved membrane stability. Grain yield retention increased from below 50% to above 72% under drought and from 53% to 77% under salinity. The consistency of these effects across stress types and

varieties supports silicon as a broadly applicable agronomic tool for cereal crop management under climate-driven stress conditions. Future work should examine optimal application timing, field-scale dose-response relationships, and potential interactions with other mineral nutrition strategies.

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