

Article

Exogenous Silicon Alleviates Saline–Alkali Stress in Melon Seed Germination via Antioxidant and Starch Metabolism

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Abstract

Soil salinization critically restricts melon production, and the seed germination stage is particularly vulnerable to saline–alkali stress (SAS). Although silicon (Si) is known to enhance plant stress tolerance, its role in alleviating SAS-induced inhibition of melon seed germination—particularly under combined neutral and alkaline salt stress—remains insufficiently characterized. Here, using the melon cultivar ‘Xinyinhui’, we simulated SAS with a mixture of NaCl and NaHCO₃ and screened for the optimal Si concentration. We then systematically examined physiological, biochemical, and gene expression responses. SAS significantly inhibited germination (20.4% reduction in germination rate; 56.9% in vigor index) and induced oxidative damage (MDA increased by 9.7%; superoxide anion by 170.6%), suppressed antioxidant enzyme activities (SOD –28.8%, POD –69.4%), and disturbed starch metabolism. Exogenous Si at 1.25 mmol·L^{−1} effectively alleviated these effects: The germination rate increased from 71.7% to 88.8%, and SOD and POD activities increased by 26.7% and 63.6%, while MDA and superoxide anion decreased by 7.1% and 16.4%. Si also promoted starch degradation, as indicated by a 13.9% reduction in starch content, 8.4% increase in total amylase activity, and 23.2% upregulation of *CmBMY* expression. In addition, Si significantly improved root morphology: Root surface area, volume, branch number, and tip number increased by 19.8–326.3%, while the average root diameter decreased by 24.4%. These results suggest that exogenous Si alleviates SAS inhibition of melon seed germination through coordinated regulation of antioxidant defense and starch metabolism rather than through a single pathway. Our findings provide a physiological basis for the potential application of Si fertilizer in melon cultivation under saline–alkali conditions.

Keywords: antioxidant defense; Gompertz model; *Cucumis melo* L.; NaCl–NaHCO₃-combined stress; starch mobilization; coordinated regulation



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1. Introduction

Melon (*Cucumis melo* L.) is a high-value horticultural crop widely cultivated worldwide, with an annual production over 30 million tons and a planting area of approximately 1.2 million hectares. However, continuous cropping obstacles and improper water and fertilizer management have led to increasingly severe soil salinization, which has become a key environmental factor restricting the sustainable development of the melon industry.

Soil salinization is a global environmental issue. Saline–alkali stress (SAS) is the combined stress of neutral salt (mainly NaCl) and alkaline salt (mainly NaHCO₃/Na₂CO₃).

Compared with single neutral salt stress, combined SAS is more harmful to plants, as the alkaline component causes ion toxicity, osmotic stress, and high-pH-induced metabolic disruption [1,2]. Studies on cucumber and rice have shown that alkaline salts such as NaHCO_3 and Na_2CO_3 significantly inhibit seed germination, reduce amylase activity, and increase membrane lipid peroxidation [1,2].

The inhibitory effects of salt stress on melon seed germination have been widely documented. Under NaCl stress alone, increasing concentrations limit germination percentages and rates by reducing water uptake and causing ion toxicity [3], and they induce significant increases in superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) activities, indicating reactive oxygen species (ROS) overproduction and an activated enzymatic antioxidant response [4]. Combined SAS ($\text{NaCl}:\text{NaHCO}_3$) has been shown to significantly inhibit germination rates, germination potential, and α -amylase activity in melon seeds, with inhibition severity increasing with the proportion of alkaline salt [5]. Our previous work similarly confirmed that $50 \text{ mmol}\cdot\text{L}^{-1} \text{ NaCl} + 25 \text{ mmol}\cdot\text{L}^{-1} \text{ NaHCO}_3$ substantially suppresses the germination index and vigor index in melon seeds [6,7]. However, most existing studies on melon have focused on single NaCl stress, and the specific mechanisms by which combined SAS inhibits melon seed germination—and whether exogenous silicon can alleviate this inhibition—remain insufficiently explored.

Seed germination is the most critical stage in the plant life cycle, as it directly determines seedling establishment and yield formation. Germination involves water uptake, respiration activation, reserve mobilization, and radicle protrusion [8]. Two core physiological events determine germination success: energy metabolism, in which starch is hydrolyzed into soluble sugars by α - and β -amylase to fuel radicle growth [9]; and redox balance, i.e., the balance between ROS production and scavenging. Moderate ROS levels act as signaling molecules to promote germination, whereas excessive accumulation causes membrane lipid peroxidation [10]. Under salt stress, melon seed germination is typically inhibited, with reduced germination rates and radicle growth [11]; severe stress also reduces root and shoot lengths [3].

Silicon (Si) is the second most abundant element in the Earth's crust and is widely recognized as a beneficial substance for plants. Exogenous Si effectively enhances plant resistance to various stresses, including salinity, drought, extreme temperatures, and heavy metals [12]. The mechanisms of Si action involve physical barrier formation in the cell wall, enhancing antioxidant enzyme activities, ROS scavenging, and accumulation of osmotic regulatory substances [13]. During seed germination, Si has been shown to increase germination rates and amylase activity in fenugreek under salt stress [14], promote amylase activities in lentil under osmotic stress [15], upregulate *AMY* and *BMV* expression and promote starch hydrolysis in cucumber [16], and increase amylase activities in melon under autotoxicity stress [11]. Simultaneously, Si enhances SOD, POD, CAT, and ascorbate peroxidase (APX) activities in tomato seeds under water stress [17], improves antioxidant enzyme activities in cucumber seed under salt stress [18], increases SOD and PPO activities in fenugreek [14], promotes maize germination via enhancing antioxidant defense [19], and improves germination through seed priming under salt stress [20,21]. Lettuce studies also confirm that Si alleviates salt-induced germination inhibition by enhancing antioxidant responses [22]. Notably, amorphous silica nanoparticles can catalyze ROS production through surface silanol and siloxane groups, initiating redox signaling and activating stress-responsive genes [23]. In melon specifically, Si priming improves germination and seedling growth under NaCl stress [24], and Si applications alleviate autotoxicity stress by promoting starch degradation and enhancing antioxidant enzyme activities [11]. Despite these advances, most existing studies have focused on single stress types and have investigated either the antioxidant system [17,20] or starch metabolism [9] in isolation.

Seed germination requires the coordinated operation of energy metabolism and redox balance, yet these two core pathways have not been sufficiently analyzed within the same framework of combined SAS. Therefore, the specific effects and regulatory mechanisms of Si on melon seed germination under combined SAS remain unclear.

Based on the above analysis, we hypothesize that exogenous Si alleviates the inhibition of melon seed germination under SAS in a concentration-dependent manner and that this alleviation is achieved through the simultaneous regulation of starch metabolism and the antioxidant defense system. To test this hypothesis, melon cultivar ‘Xinyinhui’ was used, and combined SAS was simulated with 50 mmol·L⁻¹ NaCl and 25 mmol·L⁻¹ NaHCO₃. A gradient concentration experiment (0.5–2.5 mmol·L⁻¹ Si) was conducted to screen the optimal exogenous Si concentration, and the effects of Si on germination parameters, antioxidant enzyme activities, malondialdehyde (MDA) and O₂^{-·} contents, amylase activities, and gene expression, as well as starch and soluble sugar contents, were systematically analyzed. This study tests this hypothesis by examining the coordinated regulation of starch metabolism and antioxidant defense by Si during melon seed germination under combined SAS.

2. Materials and Methods

2.1. Plant Material and Reagents

The melon (*Cucumis melo* L.) cultivar used in this study was ‘Xinyinhui’. Seeds were purchased from Fujian Nongjia Seed Co., Ltd. (Fuzhou, China). Uniformly full and intact seeds of a similar size were selected for all experiments.

Sodium chloride (NaCl), sodium bicarbonate (NaHCO₃), and sodium metasilicate nonahydrate (Na₂SiO₃·9H₂O) were used for treatment preparation. All reagents were of analytical grade.

2.2. Seed Sterilization and Sowing

Before treatment, seeds were surface-sterilized with 75% ethanol for 30 s, followed by 0.5% NaClO (containing 0.05% Tween-20) for 3 min, and then rinsed six times with sterile distilled water. The sterilized seeds were placed in sterile Petri dishes (90 mm diameter) lined with two layers of filter paper, with 20 seeds per dish. Each dish received 4 mL of treatment solution and was sealed with parafilm to maintain moisture and allow limited gas exchange. The Petri dishes were placed in a temperature-controlled incubator (28 ± 1 °C) in complete darkness throughout the germination period; the dishes were covered with aluminum foil to ensure darkness. Relative humidity inside the sealed dishes was maintained by a saturated atmosphere. Germination was recorded daily under a green safe light to avoid light exposure during scoring.

2.3. Experimental Design

2.3.1. Determination of SAS Concentration

The appropriate concentration for combined SAS was determined based on preliminary experiments. A series of concentration combinations was set up, with 0, 25, 50, 75, and 100 mmol·L⁻¹ NaCl and corresponding proportions of NaHCO₃ (NaCl: NaHCO₃ = 2:1, molar ratio). Each treatment had three replicates with 20 seeds per replicate. Distilled water was used as the control (CK). Germination percentage, radicle length, and radicle morphology were recorded.

According to the widely adopted “moderate stress” principle (inhibition rate of 30–50%), the treatment of 50 mmol·L⁻¹ NaCl + 25 mmol·L⁻¹ NaHCO₃ was selected for subsequent experiments. Distilled water was used as a control (CK) to provide a baseline for evaluating the overall inhibitory effect of SAS and the alleviating effect of Si. The

measured pH of this solution was 8.31 ± 0.05 ($n = 10$), and electrical conductivity was $8.23 \pm 0.12 \text{ mS}\cdot\text{cm}^{-1}$ ($n = 10$, 25°C).

2.3.2. Screening of the Optimal Si Concentration

Eleven treatments were established, each with three biological replicates of 20 seeds per replicate: CK (distilled water); SA ($50 \text{ mmol}\cdot\text{L}^{-1} \text{ NaCl} + 25 \text{ mmol}\cdot\text{L}^{-1} \text{ NaHCO}_3$); and SA + Si. In total, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, and $2.5 \text{ mmol}\cdot\text{L}^{-1}$ Si were added to SA (Table 1). Si was supplied as $\text{Na}_2\text{SiO}_3\cdot 9\text{H}_2\text{O}$. A stock solution ($100 \text{ mmol}\cdot\text{L}^{-1}$ Si) was prepared and stored at 4°C in the dark and then diluted to target concentrations before use. The pH of all treatment solutions was adjusted to 8.30 ± 0.05 using $0.1 \text{ mol}\cdot\text{L}^{-1}$ HCl or NaOH.

Table 1. Experimental treatments used in this study.

Treatment Code	NaCl ($\text{mmol}\cdot\text{L}^{-1}$)	NaHCO ₃ ($\text{mmol}\cdot\text{L}^{-1}$)	Si ($\text{mmol}\cdot\text{L}^{-1}$)	Description
CK	0	0	0	Distilled water control
SA	50	25	0	Saline-alkali stress
SA + 0.5 Si	50	25	0.5	SAS + $0.5 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 0.75 Si	50	25	0.75	SAS + $0.75 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 1.0 Si	50	25	1.0	SAS + $1.0 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 1.25 Si	50	25	1.25	SAS + $1.25 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 1.5 Si	50	25	1.5	SAS + $1.5 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 1.75 Si	50	25	1.75	SAS + $1.75 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 2.0 Si	50	25	2.0	SAS + $2.0 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 2.25 Si	50	25	2.25	SAS + $2.25 \text{ mmol}\cdot\text{L}^{-1}$ Si
SA + 2.5 Si	50	25	2.5	SAS + $2.5 \text{ mmol}\cdot\text{L}^{-1}$ Si

The dishes were arranged in a completely randomized design, and their positions were randomly changed every 24 h. The filter paper and treatment solution were replaced every 48 h (on days 2 and 4) to maintain stable treatment concentrations and avoid microbial contamination; during replacement, seedlings were transferred together with the upper layer of filter paper to new Petri dishes containing fresh treatment solution and sterile filter paper. Radicle protrusion of 2 mm was used as the criterion for germination. Germination was recorded every 24 h. The experiment was terminated when no new germination was observed for three consecutive days, which occurred on day 6.

Growth Measurements: Each day, five randomly selected seeds per treatment were destructively sampled for weighing (precision 0.0001 g) and radicle length measurement (precision 0.5 mm). On day 6 (144 h after treatment initiation), ten seedlings per replicate were scanned using a root scanner (Epson Perfection 4990 PHOTO), and images were analyzed with WinRHIZO software (version Pro 2019a) (Regent Instruments Inc., Quebec, QC, Canada). Root surface area (cm^2), average diameter (mm), volume (mm^3), branch number, and tip number were recorded.

2.3.3. Criteria for Selecting the Optimal Concentration

The membership function method was used to evaluate the comprehensive performance of all germination and root parameters. The membership value for each indicator was calculated as $(X - X_{\min}) / (X_{\max} - X_{\min})$. The average membership value across all indicators was calculated for each treatment, and the treatment with the highest average membership value was selected as optimal. This method enables the integration of multiple indicators with different units and scales into a single composite score, providing an objective criterion for selecting the optimal treatment. Based on this method, $1.25 \text{ mmol}\cdot\text{L}^{-1}$ Si was determined as the optimal concentration.

2.3.4. Experimental Design for Physiological Mechanism Study

Three treatments were established: CK (distilled water); SA (50 mmol·L⁻¹ NaCl + 25 mmol·L⁻¹ NaHCO₃, pH 8.30 ± 0.05); and SA + Si (SA + 1.25 mmol·L⁻¹ Si, pH 8.30 ± 0.05), each with three biological replicates of 20 seeds. The culture method was the same as described in Section 2.2. Samples were collected at 0, 6, 12, 24, 48, and 96 h. Seed coats were removed, and 0.1 g of intact seed (embryo + endosperm) per replicate was frozen in liquid nitrogen and stored at −80 °C for subsequent analyses.

2.4. Measurement Indicators and Methods

2.4.1. Seed Germination Indicators

Germination percentage (%) = (Final germinated seeds/Total seeds) × 100%. Germination potential (%) = (Germinated seeds on day 3/Total seeds) × 100%. The germination index is (GI) = $\Sigma(Gt/Dt)$, where Gt is germinated seeds on day t, and Dt is the corresponding day. The vigor index is (VI) = GI × S, where S is the average radicle length (cm) on day 6.

2.4.2. Physiological and Biochemical Indicator Assays

Frozen samples were ground into fine powder in liquid nitrogen. All physiological and biochemical indicators were measured using commercial kits (Suzhou Comin Biotechnology Co., Ltd., Suzhou, China) following the manufacturers' instructions. The key parameters were as follows: SOD activity: NBT photoreduction method; one unit (U) was defined as 50% inhibition of NBT reduction per 20 min at 25 °C. The results were expressed as U·g⁻¹ FW. POD Activity: guaiacol method; one unit was defined as 0.01 change in OD₄₇₀ per minute. The results were expressed as U·g⁻¹ FW·min⁻¹. CAT Activity: UV absorption method; one unit was defined as a 0.01 decrease in OD₂₄₀ per minute. The results were expressed as U·g⁻¹ FW·min⁻¹. MDA Content: TBA method. The results were expressed as nmol·g⁻¹ FW. Superoxide Anion (O₂⁻) Content: hydroxylamine oxidation method. The results were expressed as nmol·g⁻¹ FW. Starch and Soluble Sugar Contents: anthrone-sulfuric acid method. The results were expressed as mg·g⁻¹ FW. α- and β-Amylase Activities: dinitrosalicylic acid (DNS) method; one unit was defined as 1 mg maltose produced per minute at 37 °C. The results were expressed as U·g⁻¹ FW·min⁻¹.

2.4.3. Total RNA Extraction and Real-Time Quantitative PCR

Total RNA was extracted using the RNAPrep Pure Plant Plus Kit (DP441, Tiangen Biotech Co., Ltd., Beijing, China) according to the manufacturer's instructions. RNA integrity was assessed by agarose gel electrophoresis, and concentration/purity was measured using NanoDrop 2000 spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA). One microgram of total RNA was reverse-transcribed into cDNA using the HiScript III RT SuperMix for qPCR (R323-01, Vazyme Biotech Co., Ltd., Nanjing, China).

The melon *EF1a* was used as the internal control. Its suitability as a reference gene in melon under stress conditions has been previously reported [25]. *CmAMY* and *CmBMY* were the target genes. The primers were as follows: *EF1a* forward (5'-ACTGTGCTGTCCTCATTATTG-3') and reverse (5'-AGGGTCAAAGCAAGAAGAGC-3'); *CmAMY* forward (5'-GGAAGGATCTCTGTCAAAC-3') and reverse (5'-GGTGTCTCAATAGCATAATC-3'); *CmBMY* forward (5'-AAATCTCTTGGGCTCTACAATCTCG-3') and reverse (5'-CATTCTCTGGTATGTGAACAACCTCC-3'). All primers were synthesized according to Zhang et al. [21].

RT-qPCR was performed using a QuantStudio 3 system with ChamQ Universal SYBR qPCR Master Mix (Q711-02, Vazyme Biotech). The reaction program was as follows: 95 °C for 30 s and 40 cycles of 95 °C for 10 s, 60 °C for 30 s, and 72 °C for 30 s, followed by melting

curve analysis. Each sample had three technical replicates. Relative gene expression was calculated using the $2^{-\Delta\Delta C_t}$ method, calibrated to the CK treatment at 0 h.

2.5. Data Statistics and Analysis

Data were organized using Microsoft Excel 2019 and analyzed using IBM SPSS Statistics 26.0. All data are presented as mean $\pm$ SD ($n = 3$). Normality was tested using Shapiro–Wilk and homogeneity of variances using Levene’s test. One-way ANOVA followed by Duncan’s multiple range test (or Welch’s ANOVA with Games-Howell correction when variances were unequal) was used for comparisons among treatments at the same time point. Two-way ANOVA was used to examine the effects of treatment, time, and their interaction.

Germination Kinetic Analysis: Cumulative germination curves were fitted using the Gompertz model: $G(t) = A \cdot \exp[-\exp(B - C \cdot t)]$, where $G(t)$ is the cumulative germination rate (%) at time t (h), A is the maximum germination rate (%), B is the inflection point parameter, and C is the germination rate constant. Fitting included seven time points (0, 6, 12, 24, 48, 72, and 96 h) and was performed using OriginPro 2021 with the Levenberg–Marquardt algorithm. Goodness of fit was evaluated by R^2 .

Correlation Analysis: Pearson correlation coefficients were calculated among physiological indicators ($p < 0.05$) using OriginPro 2021. Graphs were created using GraphPad Prism 8.0.

3. Results

3.1. Effects of Different Si Concentrations on Germination Characteristics of Melon Seeds Under SAS

SAS significantly inhibited the germination of melon seeds. Compared with CK, the SA treatment significantly reduced the germination percentage, germination potential, germination index, and vigor index by 20.37%, 19.23%, 30.50%, and 56.88%, respectively (Table 3). With increasing Si concentrations, all germination parameters showed a unimodal response, peaking at $1.25 \text{ mmol} \cdot \text{L}^{-1}$ Si, and they were significantly higher than those within the range of $1.0\text{--}1.5 \text{ mmol} \cdot \text{L}^{-1}$ Si in the SA treatment. Specifically, the SA + 1.25 mM Si treatment achieved a germination percentage of $88.3 \pm 5.8\%$, representing an increase of 16.6 percentage points compared with the SA treatment ($71.7 \pm 2.9\%$); the germination potential reached $85.0 \pm 5.0\%$, an increase of 15.0 percentage points over SA ($70.0 \pm 5.0\%$); the germination index and vigor index also increased significantly to 16.42 ± 0.93 and 1.08 ± 0.06 , respectively.

Table 2. Effects of different silicon concentrations on germination parameters of melon seeds under saline–alkali stress.

Treatment	Germination Percentage (%)	Germination Potential (%)	Germination Index	Vigor Index
CK (ddH ₂ O)	90.0 $\pm$ 5.0 a	86.7 $\pm$ 2.9 a	18.82 $\pm$ 0.38 a	1.60 $\pm$ 0.03 a
SA	71.7 $\pm$ 2.9 cd	70.0 $\pm$ 5.0 d	13.08 $\pm$ 1.21 de	0.69 $\pm$ 0.06 e
SA + 0.5 mM Si	66.7 $\pm$ 2.9 de	65.0 $\pm$ 5.0 e	11.33 $\pm$ 0.74 fg	0.63 $\pm$ 0.04 e
SA + 0.75 mM Si	70.0 $\pm$ 5.0 cd	63.3 $\pm$ 2.9 ef	11.89 $\pm$ 0.34 ef	0.67 $\pm$ 0.02 e
SA + 1.0 mM Si	83.3 $\pm$ 5.8 ab	76.7 $\pm$ 2.9 b	14.94 $\pm$ 0.42 c	0.96 $\pm$ 0.03 c
SA + 1.25 mM Si	88.3 $\pm$ 5.8 a	85.0 $\pm$ 5.0 a	16.42 $\pm$ 0.93 b	1.08 $\pm$ 0.06 b
SA + 1.5 mM Si	83.3 $\pm$ 2.9 ab	81.7 $\pm$ 2.9 ab	16.28 $\pm$ 0.57 b	1.00 $\pm$ 0.03 bc
SA + 1.75 mM Si	83.3 $\pm$ 2.9 ab	81.7 $\pm$ 7.6 ab	14.28 $\pm$ 1.14 cd	0.81 $\pm$ 0.06 d
SA + 2.0 mM Si	81.7 $\pm$ 2.9 ab	80.0 $\pm$ 5.0 ab	14.25 $\pm$ 1.12 cd	0.81 $\pm$ 0.06 d

Table 3. Effects of different silicon concentrations on germination parameters of melon seeds under saline–alkali stress.

Treatment	Germination Percentage (%)	Germination Potential (%)	Germination Index	Vigor Index
SA + 2.25 mM Si	76.7 ± 5.8 bc	73.3 ± 7.6 c	13.39 ± 0.82 d	0.67 ± 0.04 e
SA + 2.5 mM Si	60.0 ± 5.0 e	58.3 ± 7.6 f	10.06 ± 0.46 g	0.45 ± 0.02 f

Note: Data are presented as mean ± SD ($n = 3$). Different lowercase letters within the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range test. CK: Control; SA: saline–alkali stress.

3.2. Germination Kinetic Analysis

To further elucidate the regulatory characteristics of Si on the germination process, the Gompertz model was used to fit the cumulative germination curves of melon seeds under the 11 treatments. The fitted parameters and goodness of fit for each treatment are shown in Table 4 and Figure 1. The R^2 values for all treatments ranged from 0.985 to 0.994, indicating that the Gompertz model well described the cumulative germination dynamics of melon seeds under different treatments. For the CK treatment, the maximum germination rate A was 90.0%, the B value was 1.18, and the C value was 0.072.

Table 4. Gompertz model parameters for cumulative germination of melon seeds under different treatments.

Treatment	A (%)	B	C	R^2
CK	90.0 ± 3.5	1.18 ± 0.05	0.072 ± 0.003	0.994 ± 0.003
SA	71.7 ± 2.8	4.52 ± 0.35	0.113 ± 0.008	0.989 ± 0.005
SA + 0.5 mM Si	66.7 ± 2.2	5.68 ± 0.42	0.128 ± 0.010	0.987 ± 0.006
SA + 0.75 mM Si	72.2 ± 2.5	2.25 ± 0.28	0.062 ± 0.007	0.990 ± 0.005
SA + 1.0 mM Si	86.0 ± 2.0	1.68 ± 0.20	0.055 ± 0.006	0.993 ± 0.004
SA + 1.25 mM Si	88.8 ± 1.8	2.95 ± 0.25	0.086 ± 0.007	0.994 ± 0.004
SA + 1.5 mM Si	83.5 ± 2.1	3.08 ± 0.28	0.097 ± 0.008	0.992 ± 0.004
SA + 1.75 mM Si	83.4 ± 2.5	6.02 ± 0.48	0.136 ± 0.011	0.988 ± 0.005
SA + 2.0 mM Si	81.7 ± 2.3	5.68 ± 0.45	0.131 ± 0.010	0.989 ± 0.005
SA + 2.25 mM Si	77.0 ± 2.6	3.90 ± 0.38	0.098 ± 0.009	0.990 ± 0.005
SA + 2.5 mM Si	60.0 ± 3.0	5.63 ± 0.52	0.126 ± 0.012	0.985 ± 0.007

Note: Data are presented as mean ± SD ($n = 3$). CK: Control; SA: saline–alkali stress. A: maximum germination rate (%); B: inflection point parameter; C: germination rate constant; R^2 : coefficient of determination. Fitting was performed using the Gompertz model $G(t) = A \cdot \exp[-\exp(B - C \cdot t)]$ on individual replicates with time points 0, 6, 12, 24, 48, 72, and 96 h.

Compared with CK, the SA treatment significantly reduced the maximum germination rate to 71.7% and increased the B value to 4.52 (Table 3). After the addition of different concentrations of exogenous Si, the germination parameters changed regularly. As the Si concentration increased, the A value rose and then fell. The A values of SA + 1.0 mM Si, SA + 1.25 mM Si, and SA + 1.5 mM Si reached 86.0%, 88.8%, and 83.5%, respectively, all significantly higher than that of SA. The SA + 1.25 mM Si treatment had the highest A value, increasing by 17.1 percentage points compared with SA, approaching the CK level (90.0%).

The changes in B and C values also reflected the regulatory effect of Si on the germination process. The B value of SA (4.52) was significantly higher than that of CK (1.18). After Si addition, the B value first decreased and then increased, with the B values of SA + 1.0 mM Si (1.68), SA + 1.25 mM Si (2.95), and SA + 1.5 mM Si (3.08) being lower than those of SA. The change trend of the C value was opposite to that of the B value.

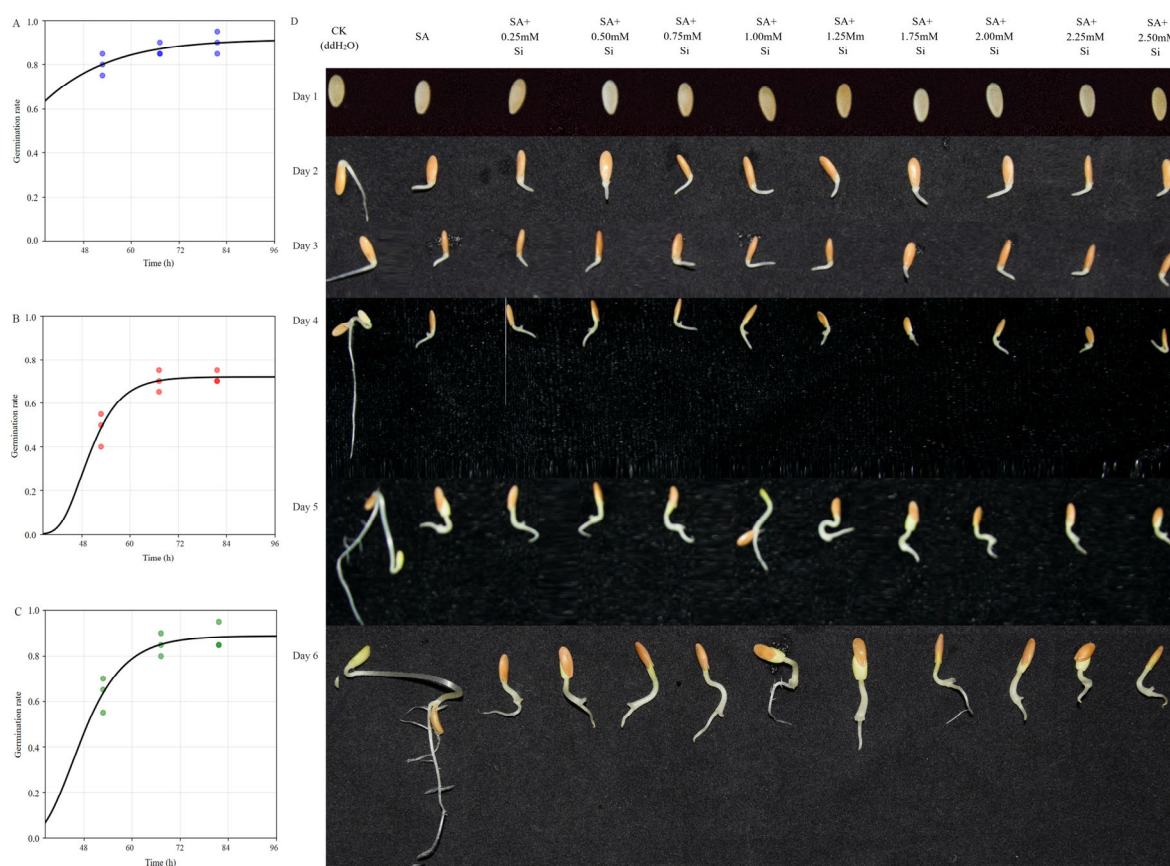


Figure 1. Gompertz fitted germination curves of melon seeds under different treatments. Note: Cumulative germination rates of melon seeds fitted with the Gompertz model $G(t) = A \cdot \exp[-\exp(B - C \cdot t)]$. Curves represent the fitted values for CK (A), SA (B), and SA + 1.25 mM Si (C) treatments. Symbols represent mean observed values ($n = 3$).

When the Si concentration was too low (≤ 0.75 mM) or too high (≥ 2.25 mM), the A value showed no significant improvement compared with SA or was even lower, such as in SA + 0.5 mM Si (66.7%) and SA + 2.5 mM Si (60.0%). The B and C values of these treatments also showed unfavorable changes.

3.3. Effects of Si on Fresh Weight, Radicle Length, and Root Morphology of Melon Seeds Under SAS

SAS also severely inhibited the radicle growth of melon seeds. As shown in Table 5, compared with CK, the SA treatment significantly reduced the root surface area, root volume, number of branches, and number of root tips by 61.79%, 74.68%, 92.61%, and 83.32%, respectively. Compared with CK, all root morphological parameters in the SA + Si treatment groups were also significantly reduced. However, compared with SA, the root surface area, root volume, number of branches, and number of root tips exhibited a unimodal response with increasing Si concentrations, all peaking at $1.25 \text{ mmol} \cdot \text{L}^{-1}$ Si. At this concentration, the root surface area, root volume, number of branches, and number of root tips increased significantly by 19.8%, 58.0%, 326.3%, and 145.2%, respectively, compared with SA. Meanwhile, the average root diameter of seeds under the SA treatment increased significantly compared with CK. After exogenous Si application, the average root diameter first decreased and then increased with increasing Si concentrations, approaching the control level at Si concentrations of 1.0 – $1.5 \text{ mmol} \cdot \text{L}^{-1}$.

Table 5. Effects of different silicon concentrations on root morphological parameters of melon seeds under saline–alkali stress.

Treatment	Root Surface Area (cm ²)	Average Root Diameter (mm)	Root Volume (mm ³)	Number of Branches	Number of Root Tips
CK (ddH ₂ O)	2.12 ± 0.21 a	0.76 ± 0.07 e	32.50 ± 1.32 a	18.00 ± 3.61 a	22.00 ± 2.00 a
SA	0.81 ± 0.01 cde	1.23 ± 0.14 cd	8.23 ± 0.93 cd	1.33 ± 0.58 de	3.67 ± 1.53 efg
SA +0.5 mM Si	0.82 ± 0.06 cde	1.24 ± 0.08 cd	8.17 ± 0.91 cd	0.67 ± 0.58 ef	3.33 ± 1.53 fg
SA +0.75 mM Si	0.85 ± 0.02 bcd	1.16 ± 0.27 cd	9.17 ± 0.38 c	2.33 ± 0.58 def	5.00 ± 1.00 de
SA +1 mM Si	0.92 ± 0.04 bc	0.94 ± 0.16 de	12.00 ± 1.32 b	3.67 ± 0.58 bc	7.33 ± 0.58 bc
SA +1.25 mM Si	0.97 ± 0.07 b	0.93 ± 0.05 de	13.00 ± 0.50 b	5.67 ± 0.58 b	9.00 ± 1.00 b
SA +1.5 mM Si	0.89 ± 0.02 bc	0.95 ± 0.06 de	9.73 ± 0.68 c	4.67 ± 1.15 bc	7.00 ± 1.00 bc
SA +1.75 mM Si	0.84 ± 0.03 bc	1.23 ± 0.23 cd	8.43 ± 0.83 cd	3.33 ± 0.58 cde	5.67 ± 0.58 cd
SA +2 mM Si	0.76 ± 0.04 def	1.35 ± 0.04 bc	7.33 ± 0.45 de	3.00 ± 1.00 cd	3.00 ± 1.00 fg
SA +2.25 mM Si	0.72 ± 0.03 ef	1.64 ± 0.28 ab	7.47 ± 0.38 de	1.67 ± 0.58 ef	2.33 ± 0.58 g
SA +2.5 mM Si	0.66 ± 0.02 ef	1.73 ± 0.13 a	6.27 ± 0.86 e	0.67 ± 0.58 f	1.33 ± 1.15 g

Note: Data are presented as mean ± SD ($n = 3$). Different lowercase letters within the same column indicate significant differences at $p < 0.05$. CK: Control; SA: saline–alkali stress without silicon; SA + Si: saline–alkali stress with different silicon concentrations.

Melon seeds began to germinate on the second day after treatment. As shown in Figure 2, over time, fresh weight and radicle length in different treatment groups increased at different rates, with faster growth from days 2 to 4 and slower growth after day 4. Except for fresh weight on days 1 and 2, the fresh weight and radicle length of CK were consistently greater than those of the other treatment groups. During the experiment, fresh weight in the SA + Si treatment groups showed a unimodal response with increasing Si concentrations, with the peak at 1.25 mmol·L^{−1} Si. Except for day 3, the peak values at other time points were significantly higher than those in the SA group. Except for day 3, fresh weight at Si concentrations in the range of 0.75–2.0 mmol·L^{−1} was higher than that in the SA group at the same time point, whereas fresh weight at Si concentrations ≤ 0.75 mmol·L^{−1} or >2.0 mmol·L^{−1} was lower than that in SA. The changing trend in radicle lengths was similar to that of fresh weight. On days 5 and 6, the radicle length in the 1.25 mmol·L^{−1} Si treatment group was significantly higher than that in all other treatment groups except CK.

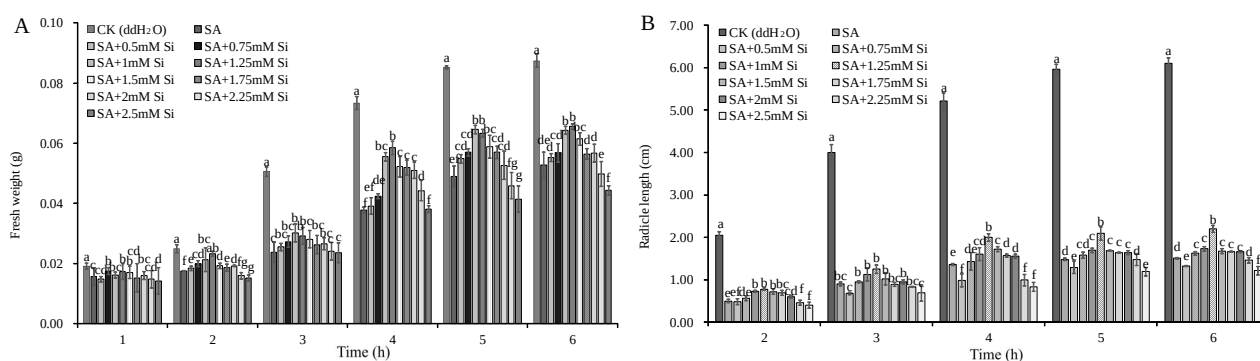


Figure 2. Dynamics of fresh weight and radicle length of melon seeds under different silicon concentrations. Note: Changes in fresh weight (A) and radicle length (B) of melon seeds during germination under saline–alkali stress with different silicon concentrations. Data points represent mean ± SD ($n = 3$). CK: Control; SA: saline–alkali stress; SA + 0.5 to SA + 2.5 mM Si: saline–alkali stress supplemented with 0.5 to 2.5 mM silicon. Different lowercase letters indicate significant differences among treatments at the same time point ($p < 0.05$).

3.4. Effects of Si on Reactive Oxygen Species and Protective Enzymes During Melon Seed Germination Under SAS

Exogenous Si significantly enhanced antioxidant enzyme activities and reduced ROS and MDA levels in melon seeds under saline–alkali stress (Figure 3). During the 96 h of seed germination, SOD activity in all three treatments peaked at 12 h, at which point SOD activities in SA and SA + Si were significantly lower than that in CK (Figure 3A). At 24 and 48 h, no significant differences in SOD activity were observed among the three treatments. SOD activity in SA showed no significant changes at 48 and 96 h, whereas SOD activities in CK and SA + Si at 96 h were significantly higher than those at 48 h. At 96 h, SOD activity in SA was significantly lower than that in CK and SA + Si, decreasing by 28.77% and 21.35%, respectively.

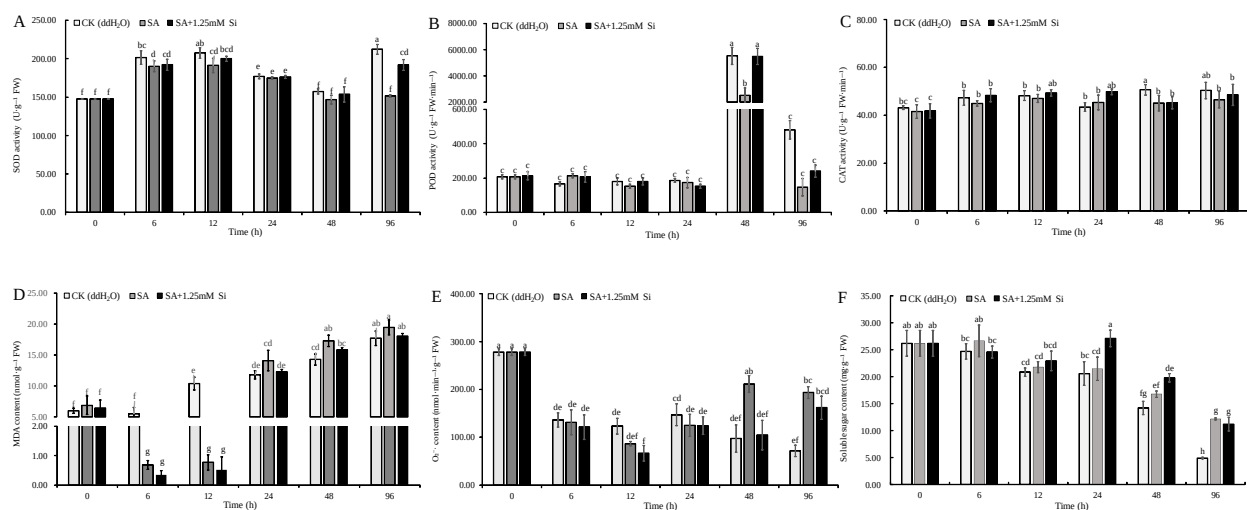


Figure 3. Effects of silicon on antioxidant-related physiological parameters during melon seed germination under saline–alkali stress. Note: Time-course changes in SOD activity (A), POD activity (B), CAT activity (C), MDA content (D), superoxide anion ($O_2^{\cdot-}$) content (E), and soluble sugar content (F) in germinating melon seeds under different treatments. Seeds were treated with CK, SA, or SA + Si. Samples were collected at 0, 6, 12, 24, 48, and 96 h after treatment. Data are presented as mean $\pm$ SD ($n = 3$). Different lowercase letters indicate significant differences among treatments at the same time point ($p < 0.05$).

Within the first 24 h, POD activity remained stable with no significant changes (Figure 3B). At 48 h, when seeds began to germinate, POD activity in all treatments increased sharply. POD activity in SA was significantly lower than that in CK and SA + Si, decreasing by 69.4% and 38.9%, respectively, while no significant difference was observed between CK and SA + Si. At 96 h, POD activity in all three treatments decreased to the level of 0–24 h, with CK slightly higher than SA and SA + Si, but the differences were not significant.

During 96 h of seed germination (Figure 3C), CAT activity exhibited a pattern of increase, followed by a slight decrease and then a slight increase. The peaks for CK and SA occurred at 12 h, while the peak for SA + Si occurred at 24 h. At 6, 12, and 96 h, CAT activity in SA was lower than that in CK and SA + Si, but the differences were not significant. At 48 h, CAT activity in CK was significantly higher than that in SA and SA + Si, increasing by 11.02% and 10.69%, respectively, while no significant difference was observed between SA and SA + Si.

Under CK treatment, MDA contents showed no significant change from 0 to 6 h but continuously increased from 6 to 96 h (Figure 3D). Under SA and SA + Si treatments, the MDA content was much lower than that of CK at 6 and 12 h but continuously increased

from 24 to 96 h. At 24, 48, and 96 h, MDA content in the SA treatment was consistently higher than that in CK and SA + Si but only significantly different from CK at 48 h.

Superoxide anion ($O_2^{\cdot-}$) content in all three treatments decreased sharply, then slightly increased, and then slowly decreased over time (Figure 3E), with the lowest values occurring at 12 h. At 0, 6, and 24 h, no significant differences were observed among the three treatments. At 48 h, $O_2^{\cdot-}$ contents in the SA treatment were 2.18-fold and 2.03-fold higher than those in CK and SA + Si, respectively, with significant differences. At 96 h, the $O_2^{\cdot-}$ content in the SA treatment was significantly higher than that in CK but not significantly different from SA + Si.

Soluble sugar content during seed germination showed a similar trend to starch content, gradually decreasing overall (Figure 3F). In the SA + Si treatment, soluble sugar content slowly decreased from 0 to 12 h, rebounded slightly at 24 h, and then decreased rapidly. At 6 h, soluble sugar content in SA was slightly higher than that in CK and SA + Si, but the differences were not significant. At 24 and 48 h, the soluble sugar content in SA + Si was higher than that in CK and SA, with a significant difference at 24 h. At 96 h, the soluble sugar content in CK was much lower than that in SA and SA + Si, decreasing by 58.33% and 54.55%, respectively.

3.5. Effects of Si on Starch Metabolism During Melon Seed Germination Under SAS

Exogenous Si influenced starch degradation, amylase activities, and related gene expression in melon seeds under saline–alkali stress (Figure 4). As treatment time increased, starch content in all three treatments showed a continuous decreasing trend (Figure 4A). From 6 to 24 h, starch contents remained relatively stable. Except at 24 and 96 h, differences in starch contents among treatments at the same time point were small. The starch content in SA was lower than that in CK and SA + Si at 24 h but higher than that in CK and SA + Si at 96 h, with a significant difference from CK.

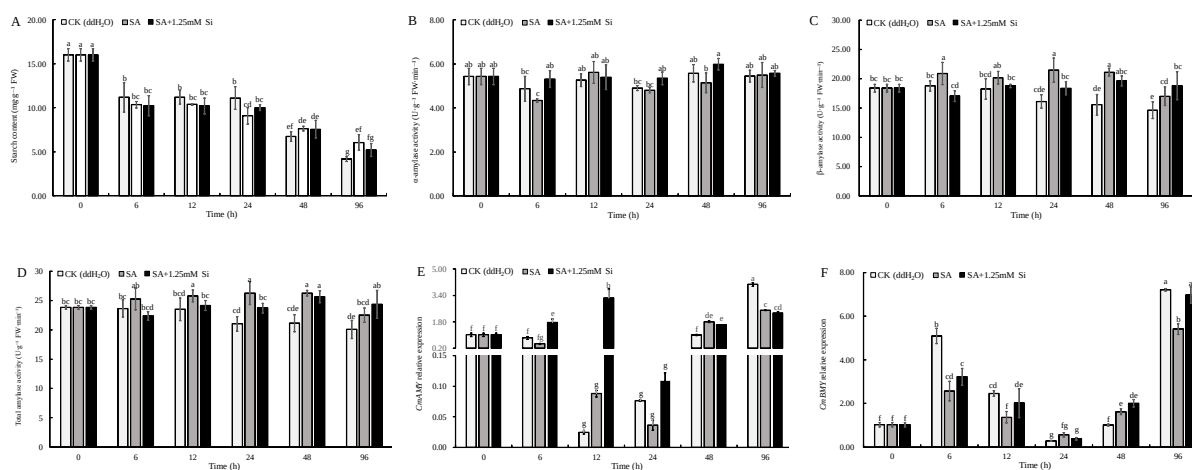


Figure 4. Effects of silicon on starch metabolism-related parameters during melon seed germination under saline–alkali stress. Note: Time-course changes in starch content (A), α -amylase activity (B), β -amylase activity (C), total amylase activity (D), CmAMY expression (E), and CmBMY expression (F) in germinating melon seeds under different treatments. Seeds were treated with CK, SA, or SA + Si. Samples were collected at 0, 6, 12, 24, 48, and 96 h after treatment. Data are presented as mean $\pm$ SD ($n = 3$). Different lowercase letters indicate significant differences among treatments at the same time point ($p < 0.05$).

As shown in Figure 4B, α -amylase activity in SA sharply decreased at 6 h, sharply rebounded to the 0 h level at 12 h, and then slightly decreased at 24 h and subsequently increased slowly. CK exhibited a fluctuating pattern: decrease at 6 h, increase at 12 h, decrease at 24 h, increase at 48 h, and stabilization at 96 h. α -amylase activity in SA + Si

remained at the 0 h level at all time points except for a slight increase at 48 h. At 6 and 48 h, α -amylase activity in SA was lower than that in CK and SA + Si, with significant differences from SA + Si.

β -amylase activity in CK showed no significant change within the first 6 h but gradually decreased after 6 h (Figure 4C). β -amylase activity in SA was significantly higher at 6 h than at 0 h, showed no significant change from 6 to 48 h, and sharply decreased at 96 h. β -amylase activity in SA + Si showed no significant change throughout the treatment period. β -amylase activity in SA was higher than that in CK and SA + Si at 6, 12, 24, and 48 h, with significant differences at 6, 24, and 48 h. At 96 h, β -amylase activity in CK was significantly lower than that in SA and SA + Si, decreasing by 11.76% and 21.05%, respectively, while no significant difference was observed between SA and SA + Si. Total amylase activity showed a similar trend to α - and β -amylase activities (Figure 4D).

Relative expression of the *CmAMY* gene in CK showed no significant change from 0 to 6 h, sharply decreased at 12 and 24 h, and sharply increased at 48 and 96 h (Figure 4E). The relative expression of *CmAMY* in SA showed an overall trend of an initial decrease followed by an increase. In SA + Si, expression sharply increased within 12 h (opposite to CK and SA), sharply decreased at 24 h, and then continuously increased. At 6 and 12 h, *CmAMY* expression in SA + Si was significantly higher than that in CK and SA at the same time points. At 48 h, *CmAMY* expression in CK was significantly lower than that in SA and SA + Si, while at 96 h, it was significantly higher than that in SA and SA + Si.

The relative expression of *CmBMY* in all three treatments exhibited an increase–decrease–increase pattern within 96 h, with the lowest values occurring at 24 h (Figure 4F). At 6, 12, and 96 h after treatment, *CmBMY* expression in SA was significantly lower than that in CK and SA + Si. At 12 and 96 h, the difference between CK and SA + Si was small. At 6 h, *CmBMY* expression in CK was significantly higher than that in SA + Si.

3.6. Correlation Analysis

Strong correlations were observed among antioxidant enzyme activities, oxidative stress indicators, starch metabolism parameters, and root morphological traits (Figure 5).

Antioxidant Enzyme System and Oxidative Stress Indicators: SOD, POD, and CAT activities showed positive correlations with each other ($r = 0.54$ – 0.73). All three were negatively correlated with MDA content ($r = -0.72$ to -0.52) and with superoxide anion content ($r = -0.90$ to -0.61). POD had the highest correlation coefficient with superoxide anion ($r = -0.90$).

Starch Metabolism-Related Indicators: Starch content showed moderate negative correlations with α -amylase ($r = -0.55$), β -amylase ($r = -0.51$), and total amylase ($r = -0.60$) activities. α -amylase, β -amylase, and total amylase showed positive correlations with each other ($r = 0.75$ – 0.94). *CmAMY* and *CmBMY* expression levels showed positive correlations with the corresponding amylase activities ($r = 0.50$ – 0.65).

Relationships Among Root Morphological Indicators: Root surface area, root volume, number of branches, and number of root tips showed strong positive correlations with each other ($r = 0.84$ – 0.95). Average root diameter showed negative correlations with these four indicators ($r = -0.70$ to -0.59).

Relationships Between Root Morphology and Physiological Indicators: The root surface area was positively correlated with POD ($r = 0.70$), CAT ($r = 0.55$), and *CmAMY* ($r = 0.48$) and negatively correlated with soluble sugar ($r = -0.53$) and O_2^- ($r = -0.74$). The average root diameter was negatively correlated with SOD ($r = -0.82$) and CAT ($r = -0.58$) and positively correlated with MDA ($r = 0.73$).

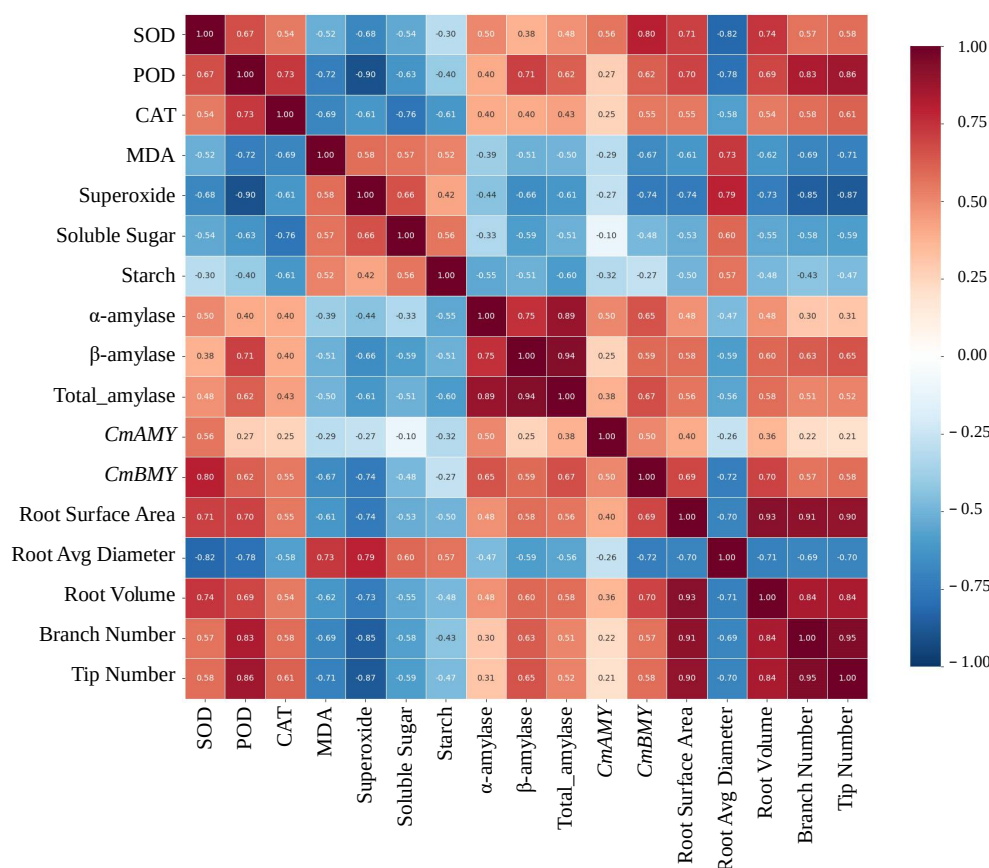


Figure 5. Correlation matrix of physiological and root morphological indicators on day 6. Note: Pearson correlation matrix of physiological and root morphological indicators on day 6. Red and blue colors indicate positive and negative correlations, respectively, with color intensity proportional to correlation strength. SOD: Superoxide dismutase; POD: peroxidase; CAT: catalase; MDA: malondialdehyde; superoxide: superoxide anion; soluble sugar: soluble sugar content; starch: starch content; α-amylase: α-amylase activity; β-amylase: β-amylase activity; total amylase: total amylase activity; Branch Number: number of branches; Tip Number: number of root tips.

4. Discussion

4.1. Exogenous Si Promotes Melon Seed Germination Under SAS

Seed germination is the most critical stage in the plant life cycle, and the germination percentage is the most direct indicator of stress alleviation. In this study, SAS significantly inhibited melon seed germination, while exogenous $1.25 \text{ mmol} \cdot \text{L}^{-1}$ Si treatment increased the germination rate from 71.7% to 88.3%. Gompertz model fitting further revealed that Si treatment reduced the inflection point parameter B and increased the maximum germination rate, A (Table 4). These kinetic parameters suggest that Si acts primarily by shortening the time required for seeds to overcome stress-induced dormancy rather than simply increasing the final germination ceiling. The concentration-dependent effect also implies that Si may function as a signaling molecule at optimal concentrations, whereas at supra-optimal levels, it may induce toxicity through excessive polymerization in the apoplast. The promotion of radicle elongation by Si likely involves multiple levels: physical protection through Si deposition in the epidermis, energy supply via enhanced starch hydrolysis, and maintenance of meristem activity through ROS homeostasis. These aspects are elaborated in the following sections.

Previous studies have confirmed the promoting effect of Si on seed germination in various species [13–15]. Specifically, in melon, the 2 mM Si treatment increased the germination percentage from 80% to 93.3% [11], and similar Si-mediated germination

enhancements have been observed in melon under salt stress. Notably, the alleviating effect exhibited a clear concentration-dependent pattern, with $1.25 \text{ mmol} \cdot \text{L}^{-1}$ identified as optimal, whereas lower or higher concentrations showed diminished or even exacerbated inhibitory effects. This pattern aligns with observations in other crop species [14,15] and underscores the importance of precise Si dosage for practical applications.

4.2. Effects of Exogenous Si on Fresh Weight and Radicle Length Dynamics of Melon Seeds

Si treatment significantly increased fresh weight and radicle length during germination (Figure 2). The promotion of radicle elongation can be attributed to multiple factors: (1) Si may stimulate cell elongation by modulating cell wall mechanical properties; (2) improved energy status from enhanced starch degradation provides ATP for cell expansion; (3) maintained ROS homeostasis prevents oxidative damage to the radicle tip. The temporal pattern—with faster growth from days 2 to 4 and slower growth thereafter—suggests that Si exerts its strongest effect during the critical phase of radicle emergence, when the seed transitions from imbibition to active growth. Consistent with these observations, Si treatment increased root length by 38.10% and root dry weight by 38.26% in melon under autotoxicity stress [7], and similar effects have been reported in cucumber under autotoxicity and cinnamic acid stress [9,26]. As the first organ to contact the external environment, rapid radicle elongation is crucial for subsequent seedling establishment and nutrient uptake in saline–alkali soils.

4.3. Effects of Exogenous Si on Root Morphology of Melon Seeds

Si treatment significantly increased root surface area, root volume, number of branches, and number of root tips while decreasing the average root diameter to levels approaching CK (Table 5). The marked increases in branch number and tip number suggest that Si enhances nutrient uptake capacity by promoting root branching. Under SA treatment, the average root diameter increased, presenting a “short and thick” morphology—a common stress response associated with inhibited cell division and restricted cell expansion [12]. Si reversed this phenotype by restoring normal root elongation. The strong positive correlations among root morphological traits ($r = 0.84\text{--}0.95$) suggest coordinated development of root system architecture. Similar improvements have been observed in lentil under osmotic stress [15] and in sea barley under salt stress [27], and they are consistent with melon studies under autotoxicity stress [7].

4.4. Exogenous Si Alleviates SAS-Induced Oxidative Damage by Enhancing the Antioxidant System

Under SAS, excessive accumulation of reactive oxygen species is a major cause of membrane lipid peroxidation and damage to the antioxidant enzyme system [12]. In this study, SA treatment significantly decreased SOD, POD, and CAT activities while greatly increasing MDA and superoxide anion contents. Si treatment restored enzyme activities and reduced oxidative damage indicators (Figure 3). Correlation analyses showed that POD had the highest correlation coefficient with superoxide anions ($r = -0.90$, Figure 5), suggesting that POD plays an important role in Si-mediated ROS scavenging. The relatively weak CAT response may be attributed to its peroxisomal localization and lower contribution during the hypoxic germination stage, whereas POD and SOD are more directly involved in the early oxidative burst triggered by SAS. This differential response also suggests that Si does not uniformly upregulate all antioxidant enzymes but rather selectively enhances those most critical for the specific stress encountered.

The mechanisms by which Si enhances antioxidant enzyme activities involve multiple levels: physical barrier formation, regulation of plasma membrane H^+ -ATPase, activation of antioxidant enzyme gene expression, and synergy with antioxidant substances [12]. The

particularly strong POD response may relate to its dual role in both ROS scavenging and cell wall lignification. These findings align with studies in tomato [17], fenugreek [14], maize [21], and alfalfa [13], and they are consistent with observations in melon under autotoxicity stress, where Si increased POD activity by 56.38% [7].

4.5. Exogenous Si Promotes Energy Supply by Regulating Starch Metabolism

Energy supply is fundamental for germination, and starch degradation into soluble sugars is the main energy source for radicle growth. In this study, Si treatment influenced starch degradation and modulated amylase activities and related gene expression (Figure 4). Correlation analysis confirmed negative associations between starch content and amylase activities ($r = -0.55$ to -0.60), while positive correlations among α -, β -, and total amylase activities ($r = 0.75$ – 0.94) indicated coordinated enzyme responses. Notably, the effects of Si were not uniformly stimulatory— β -amylase activity was often higher in SA than in SA + Si at several time points, and α -amylase did not consistently increase. This suggests that Si modulates starch metabolism in a time-dependent and enzyme-specific manner rather than universally promoting it. The overall outcome—more efficient starch mobilization for radicle growth—likely results from the coordinated timing of enzyme activities rather than from a universal increase in all amylase activities.

Consistent with these findings, Si treatment upregulated *AMY* and *BMV* expression and promoted starch hydrolysis in cucumbers under various stresses [9,16,26], and similar effects were observed in melon under autotoxicity stress [11]. Previous studies have proposed that Si may coordinate starch metabolism via the GA/ABA balance [28]. While plausible, we acknowledge that hormone levels were not directly measured; thus, this mechanism should be considered a possible explanation rather than a confirmed pathway in our experimental system.

4.6. Simultaneous Regulation: An Integrated Model of Si Action

Correlation analyses further revealed associations among root morphological indicators, antioxidant enzyme activities, and starch metabolism parameters (Figure 5). Importantly, these associations do not establish causation. The strong negative correlation between average root diameter and SOD ($r = -0.82$) indicates a statistical association but does not by itself demonstrate that Si protects root apical meristem cells through SOD activity; such a mechanism would require direct measurement of cellular markers in root tips. The coordinated nature of these responses suggests that Si acts as a systemic signal rather than a pathway-specific modulator, consistent with its proposed role as a beneficial element that primes multiple defense systems simultaneously [13].

In summary, the evidence suggests that Si alleviates SAS inhibition of melon seed germination by coordinately influencing antioxidant defense and starch metabolism. These pathways are functionally coupled: Enhanced ROS scavenging may protect amyloplast integrity and preserve amylase catalytic activities. Seed germination requires coordinated energy metabolism and redox balance, and these pathways should be studied in an integrated manner.

Several limitations should be considered. Although this study involved only a single cultivar, 'Xinyinhui', genotype-dependent Si responses have been documented in melon and other species [15,29,30], so multi-cultivar validation is needed. The absence of a Si-only treatment, the use of three biological replicates, and the lack of hormone measurements (GA/ABA) mean that the proposed GA/ABA mechanism and some interpretations remain speculative. Additionally, the NaCl-NaHCO₃ mixture does not fully replicate field saline-alkali complexity; field validation would be necessary before practical recommendations can be made.

5. Conclusions

This study confirms that exogenous Si effectively alleviates the inhibition of melon seed germination under combined SAS, with a concentration-dependent alleviation effect and an optimal concentration of $1.25 \text{ mmol} \cdot \text{L}^{-1}$. At this optimal concentration, exogenous Si acts through the coordinated regulation of two pathways: the antioxidant defense system and starch metabolism. On the one hand, it enhances the activities of SOD, POD, and CAT, reduces the accumulation of MDA and superoxide anion, and alleviates oxidative damage. On the other hand, it promotes starch degradation, increases amylase activity, and upregulates the expression of CmBMY, providing energy for radicle growth. The coordinated action of these two pathways significantly improves root morphology and ultimately increases the seed germination rate from 71.7% to 88.3%. These findings provide a physiological basis for the potential application of Si fertilizers in saline–alkali melon cultivation. However, the use of a single cultivar, controlled laboratory conditions, and the absence of Si uptake and hormone measurements limit broader applicability. Additionally, the confounding effects of Na^+ introduced via Na_2SiO_3 warrant attention. Future field trials and multi-cultivar comparisons are needed to establish a more comprehensive framework for Si application in saline–alkali melon production.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SAS	Saline–alkali stress
Si	Silicon
ROS	Reactive oxygen species
MDA	Malondialdehyde
SOD	Superoxide dismutase
POD	Peroxidase
CAT	Catalase
GA	Gibberellin
ABA	Absciscic acid
FW	Fresh weight
TBA	Thiobarbituric acid
NBT	Nitroblue tetrazolium
DNS	Dinitrosalicylic acid
qPCR	Quantitative real-time polymerase chain reaction
RT-qPCR	Reverse transcription quantitative real-time PCR
EF1 α	Elongation factor 1-alpha
CmAMY	<i>Cucumis melo</i> alpha-amylase gene
CmBMY	<i>Cucumis melo</i> beta-amylase gene
ANOVA	Analysis of variance

SD	Standard deviation
R ²	Coefficient of determination

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