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Silicon-based adaptive approaches to enhance cotton (*Gossypium hirsutum* L.) resilience under salinity stress

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Abstract

Background Cotton (*Gossypium hirsutum* L.) production in arid and saline soils is severely constrained by multiple abiotic and biotic stresses. To enhance stress resilience, this study evaluated the physiological and biochemical effects of three preparations, Aminosid-Aton, Bionitrogen, and the silicon-based Aminosid-Silicon, on a cotton variety, Bukhara-8, grown under salinity stress.

Results Under laboratory conditions, all preparations enhanced early seedling vigor compared with the untreated control, with Aminosid-Silicon producing the strongest response, resulting in an approximately 2.50-fold increase in shoot height and a 2.70-fold increase in root length. Under saline field conditions, seed germination increased from 78.30% in the control to 88.80%, 93.10%, and 96.30% in the Aminosid-Aton, Bionitrogen, and Aminosid-Silicon treatments, respectively, representing increases of 10.5, 14.8, and 18.0 points. Antioxidant enzyme activities were significantly enhanced by all preparations. Compared with the control, peroxidase, catalase, and phenylalanine ammonia-lyase activities increased by up to 12.60%, 26.20%, and 82.50%, respectively, with the highest values consistently observed in Aminosid-Silicon-treated seedlings. Flavonoid and proline accumulation increased under all treatments, with the highest values recorded under the Aminosid-Silicon treatment, where flavonoid and proline contents increased by 15.40% and 28.80%, respectively, compared with the control. Silicon application strongly stimulated superoxide dismutase activity in cotton integuments at early developmental stages. Superoxide dismutase activity increased by 14.80% at 20 days after the treatment and reached a maximum of 86.13 U·mg⁻¹ protein at 30 days after the treatment, representing a 10.00% increase over the control. This early enhancement of antioxidant activity was associated with fiber initiation occurring approximately 10 days earlier than in untreated plants. In addition, the silicon-based treatment significantly improved fiber quality parameters, including the spinning consistency index (+8 units), upper half mean length (+1.7 mm), and fiber strength (+2.3 cN·tex⁻¹), while reducing the short fiber index. The application of preparations, particularly Aminosid-Silicon, significantly reduced pest infestation, with total infestation declining from 22.4% in the control to 11.7%. Under saline and arid field conditions, seed cotton yield increased from 3 830 to 4 620 kg·hm⁻² in the control to 4 620 kg·hm⁻² in Aminosid-Silicon-treated plots, representing a 20.6% improvement.

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Conclusions Among the tested preparations, Aminosid-Silicon demonstrated the greatest efficacy in enhancing early seedling development, antioxidant defense capacity, non-enzymatic metabolite accumulation, fiber quality, pest resistance, and yield under stress conditions. These findings highlight the potential of silicon-based preparations as an effective and environmentally sustainable strategy for improving cotton productivity in saline and arid environments.

Keywords Climate change, Soil degradation, Abiotic stress, Biotic stress, Silicon preparation, Cotton, Biochemical processes, Yield

Introduction

Global climate change has become a major stress factor affecting both plants and soils in recent decades (Weiskopf et al. 2020). Rising temperatures, altered precipitation patterns, and the increasing frequency of drought events have negatively impacted the physical, chemical, and biological properties of soils (Mondal 2021). The primary consequences of these changes include soil erosion, reduced organic matter content, salinization, and declines in microbial activity (Yuan et al. 2024; Oishy et al. 2025). Soil degradation processes are intensifying worldwide and are now considered among the most serious threats to agricultural productivity (Saleem et al. 2025). These challenges are particularly severe in arid and semi-arid regions, where the extent of degraded soils continues to increase annually. As a result, climate change-driven soil degradation has emerged as a critical barrier to sustainable agriculture (Saleem et al. 2025).

Abiotic and biotic stress factors significantly influence seed germination, plant growth, and developmental processes, ultimately reducing both yield and quality (Atta et al. 2023). Abiotic stresses, such as high temperatures, drought, salinity, heavy metal contamination, and nutrient deficiency, disrupt plant physiological functions, while biotic stressors, including pathogenic microorganisms, parasitic nematodes, and insect pests, further exacerbate yield losses (Nawaz et al. 2023). Under both abiotic and biotic stress conditions, plants exhibit enhanced production of reactive oxygen species (ROS), including superoxide anions (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($\bullet OH$). Excessive ROS accumulation leads to oxidative stress, resulting in damage to proteins, lipids, and DNA and ultimately compromising cellular structural integrity (Zhou et al. 2017). To mitigate ROS-induced damage and maintain cellular homeostasis, plants activate antioxidant defense systems, which represent the primary biochemical response to stress (Mishra et al. 2023; Halliwell 2024).

Among these defense mechanisms, the enzymatic antioxidant system plays a central role, with peroxidase (POD) acting as a key enzyme that decomposes hydrogen peroxide (H_2O_2) by oxidizing phenolic substrates, thereby converting H_2O_2 into water and molecular oxygen

(Jomova et al. 2024). In addition, POD contributes to lignin biosynthesis, thereby strengthening cell walls and enhancing resistance to mechanical damage, pest attack, and environmental stress (Kim et al. 2008; Minibayeva et al. 2015). Catalase (CAT), which exhibits one of the highest reaction rates among antioxidant enzymes, catalyzes the decomposition of hydrogen peroxide into water and oxygen, thereby preventing its excessive accumulation and protecting cells from prolonged oxidative stress (Sharma et al. 2024). Phenylalanine ammonia-lyase (PAL) is another key enzyme that initiates the phenylpropanoid pathway, leading to the synthesis of diverse protective secondary metabolites (Dong et al. 2021; Ninkuu et al. 2025). PAL catalyzes the conversion of phenylalanine to cinnamic acid, a precursor for phenolic compounds, flavonoids, and lignin (Pokharel et al. 2021). These metabolites play essential roles in pathogen defense, ultraviolet radiation protection, and the mitigation of oxidative stress (Irankhahi et al. 2024).

Under salinity and drought stress, the synthesis of proline, a key osmoprotectant, is markedly enhanced in plant tissues (Hayat et al. 2021). Proline contributes to osmotic adjustment, protects membrane integrity, enhances the synthesis of stress-related proteins, and mitigates ROS toxicity. Furthermore, proline serves as an energy source during post-stress recovery and facilitates rapid plant regeneration processes (Tiware 2024). The coordinated activity of antioxidant enzymes and protective metabolites enhances plant stress tolerance, maintains intracellular homeostasis, and supports plant survival and productivity under unfavorable environmental conditions (Hayat et al. 2012).

Alongside enzymatic antioxidant defenses and osmoprotectants, plants also utilize non-enzymatic antioxidant secondary metabolites to enhance stress tolerance. Among these, flavonoids play a particularly significant role in plant stress responses (Shah et al. 2020). Flavonoids are polyphenolic compounds with strong antioxidant properties, synthesized *de novo* in plants in response to environmental stimuli. Under stress conditions such as drought, high temperatures, salinity, UV radiation, or pathogen invasion, flavonoid biosynthesis is markedly upregulated (Patil et al. 2024). In addition

to their antioxidant function, flavonoids are involved in stress signaling pathways, modulate gene expression, and activate plant defense mechanisms.

Over recent decades, silicon-based preparations have gained attention as adaptive tools for enhancing soil biological activity, restoring soil fertility, and improving plant resistance through enhanced nutrient uptake and physiological regulation (Mamasolieva et al. 2024). Under stress conditions, silicon exerts multiple beneficial effects on plants. It is incorporated into cell walls, enhancing mechanical strength (Fauteux et al. 2005); regulates stomatal function to improve water-use efficiency and drought tolerance (Malik et al. 2021); and helps maintain redox balance by mitigating ROS-induced damage, thereby preserving cellular structural and biochemical integrity (Mitani 2005). The availability and chemical forms of silicon in soil are key factors influencing plant growth, development, and stress resistance (Kumar et al. 2022). In soils where bioavailable silicon is deficient, the application of silicon-based products has been increasingly adopted worldwide due to their effectiveness in enhancing plant growth and stress tolerance (Mamasolieva et al. 2023). Thus, silicon functions not only as a nutrient amendment but also as an environmentally sustainable agricultural input (Tayade et al. 2022).

Overall, the findings suggest that silicon-based preparations are increasingly recognized as a strategic tool for stabilizing agricultural systems under climate change, preserving crop yield and quality, and mitigating stress-related impacts (De Souza Júnior et al. 2022; Yuan et al. 2024).

Therefore, this study aimed to evaluate the effectiveness of silicon-based agrotechnological approaches in enhancing the tolerance of cotton (*Gossypium hirsutum* L.) to abiotic and biotic stresses under climate change and soil degradation conditions. Specifically, the study examined the effects of silicon application on antioxidant defense mechanisms, osmoprotectant accumulation, physiological performance, and key agronomic traits, including yield and fiber quality, under saline and arid field conditions. It was hypothesized that silicon application enhances antioxidant defense systems and promotes proline accumulation, thereby improving stress tolerance as well as yield and fiber quality in cotton.

Materials and methods

Experimental site and design

Field experiments were conducted in cotton fields in the Bukhara District, Uzbekistan (39.73143° N, 64.37334° E). The soils are moderately saline, belong to the meadow-alluvial group, and exhibit a layered lithological profile with a predominantly medium- to light-loam texture. Physical clay content ranges from 19.2% to 33.4%, and bulk density varies between 1.35 and 1.50 g·cm⁻³. Their

morphological, physicochemical, and biological properties have developed under the combined influence of natural conditions and long-term agricultural activity (Aripov et al. 2023; Aytmuratova et al. 2024). In the 0–30 cm layer prior to sowing, soils were of the sulfate type and moderately saline, with an electrical conductivity (EC_e) of 2.1 ± 0.3 dS·m⁻¹, pH 7.8 ± 0.1 , and low humus content of 0.96%. Total nutrient contents ranged from 0.002% to 0.079% for nitrogen (N), 0.080%–0.658% for phosphorus (P), and 0.317%–1.560% for potassium (K). The available nutrient levels were 11.1–28.4 mg·kg⁻¹ for nitrate-N (N-NO₃), 15.6–22.3 mg·kg⁻¹ for available P (P₂O₅), and 209.1–369.5 mg·kg⁻¹ for exchangeable K (K₂O). Irrigation was performed using the regional furrow system, with water sourced from the Amu Darya River. The irrigation water had an average electrical conductivity (EC_w) of 1.29 dS·m⁻¹ and salinity of approximately 936 mg·L⁻¹, typical of moderately saline conditions in the Bukhara oasis. Cotton received five irrigations per season: one pre-flowering, three during flowering and boll-setting, and one during maturation. Individual water application rates ranged from 786 to 956 m³·ha⁻¹ per irrigation, resulting in a total seasonal irrigation amount of 3 420–4 280 m³·ha⁻¹, which is consistent with standard regional practices. The central and southern subzones of the Bukhara oasis are predominantly desert environments, while the northeastern foothill plains are arid regions. The climate is sharply continental, with hot summers and frequent dry winds (garmsel, a hot, dry wind). Recent climate change has further intensified these conditions, with the average annual temperature in Uzbekistan rising by approximately 1.6 °C, from 13.2 °C to 14.8 °C (Aripov et al. 2023).

Plant material, treatments, and experimental design

Field trials were conducted on *G. hirsutum* L. cultivar Bukhara-8, a drought-tolerant, high-yielding cotton cultivar of fiber type IV (Nematov et al. 2013). The study evaluated the effects of three preparations: Aminosit-Aton, a formulation based on para- and ortho-nitrophenolates supplemented with essential microelements; Aminosit-Silicon, the only silicon-containing treatment, containing 17% active silicon (Si), 9% total N, and balanced macro- and micronutrients; and Bionitrogen, a microbial biofertilizer containing *Azotobacter chroococcum* ($>1 \times 10^8$ CFU·mL⁻¹) in a humic peat carrier enriched with polysaccharides, vitamins, and amino acids. The control treatment received standard mineral fertilization. In field experiments, to enable a broader comparison of silicon effects under abiotic and biotic stress conditions, both a chemical preparation (Aminosit-Aton) and a biological preparation (Bionitrogen) were included in the experimental design. This design allowed for a robust evaluation of the relative effectiveness of

Aminosid-Silicon beyond comparison with the untreated control alone. The experiment covered a total area of 2 ha, with each treatment occupying 0.5 ha and being divided into three replications (1 670 m² each). Subplots of 25 m × 2.2 m (55 m²) were used for physiological and biochemical measurements. Seeds were sown on 15 April at 4–5 cm spacing within rows and 60 cm between rows, at a depth of 4–6 cm, with 15 kg of seed per treatment plot. Standard cultivation practices were followed, including two deep tillage operations (25–30 cm) and five inter-row cultivations during the vegetative stage. Theoretical plant density ranged from 333 000 to 416 000 plants·ha⁻¹; however, due to saline and arid conditions, actual plant stands were lower, though sufficient for reliable assessment. All irrigation and crop management practices were applied uniformly across treatments and followed standard regional agronomic recommendations approved by the Ministry of Agriculture of the Republic of Uzbekistan and the Institute of Cotton Breeding and Cotton Growing (<https://www.agro.uz/>). The experiment was conducted over three consecutive growing seasons (2022–2024), and the results are presented as mean values across years.

Application of preparations

Cotton seeds were primed by soaking in specially prepared containers for 24 h under dark conditions to prevent photodegradation prior to sowing. Foliar applications were subsequently performed at the square formation and flowering stages according to the treatment-specific dosages (Table 1). Sampling conducted 12 days after emergence (DAE) captured the effects of seed priming only, with foliar treatments applied subsequently at the scheduled growth stages.

Sampling and biochemical and physiological analyses

Seedling samples were collected 12 DAE for biochemical analyses. Fresh tissues were immediately frozen in liquid nitrogen and homogenized prior to analysis. Enzymatic

and biochemical parameters were quantified using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan). POD activity was determined by monitoring the formation of tetraguaiacol at 470 nm (Chance et al. 1955), while CAT activity was measured based on the decomposition of H₂O₂ at 240 nm (Aebi 1984). PAL activity was determined by measuring the formation of trans-cinnamic acid at 290 nm and calculated based on a standard curve prepared with trans-cinnamic acid (≥ 99% purity; Sigma-Aldrich) (Goldson et al. 2008). The activity of superoxide dismutase (SOD) was assessed by its ability to inhibit nitroblue tetrazolium reduction (Giannopolitis et al. 1977). In addition to enzymatic assays, total flavonoid content was measured using the aluminum chloride colorimetric method (Jia et al. 1999), total protein was estimated by the Lowry et al. (1951) method at 750 nm, and free proline content was determined using a ninhydrin-based colorimetric assay at 510 nm (Bates et al. 1973). Together, these analyses provided a comprehensive assessment of the physiological and biochemical responses of cotton seedlings under the applied treatments. Superoxide anion radicals were detected by nitroblue tetrazolium (NBT) staining. Cotton integuments collected at 20 and 40 DAE were incubated in a 0.1% NBT solution (pH 7.8) for 30 min in the dark with gentle shaking, washed with distilled water, and photographed. Staining intensity was used as a qualitative indicator of superoxide accumulation. Darker staining indicated higher superoxide accumulation (Jabs et al. 1996).

Measurements

The effects of the tested preparations on cotton seed germination, early seedling growth, morpho-phenological traits, yield, and fiber quality parameters were evaluated under controlled laboratory and field conditions.

Germination and seedling growth assessment

Germination was recorded by counting emerged seedlings at fixed time points after sowing. Seedling emergence was first observed 10 days after sowing and

Table 1 Fertilizer types and application rates for the different treatments on cotton

Treatment	Application rate/(L·ha ⁻¹)	Application stages of treatment		
		1st (seed priming)/ (cm ³ ·t ⁻¹)	2nd (foliar application during square formation)/ (mL·ha ⁻¹)	3rd (foliar application during flowering)/(mL·ha ⁻¹)
Control	–	–	–	–
Aminosid-Aton	1.2	2 000	2 000	2 000
Aminosid-Silicon	1.2	2 000	2 000	2 000
Bionitrogen	10	10 000	10 000	10 000

Seed rate was 30 kg·ha. Mineral fertilizer rate was 250 (N), 175 (P), and 125 (K) kg·ha⁻¹, respectively

subsequently monitored at regular intervals. Germination percentage was calculated as the ratio of the number of germinated seeds to the total number of seeds sown. In addition, the percentage increase relative to the control was determined. Data are presented as mean $\pm$ standard error (SE). Seedling height was measured from the base of the hypocotyl to the shoot apex, and root length was measured from the hypocotyl base to the tip of the primary root. Root system development, stem strength, and leaf vigor were assessed 12 DAE using a five-point qualitative scale (1=very weak, 5=excellent), based on ten randomly selected seedlings per replication. Root scoring considered root length, lateral root formation, and root hair density; stem scoring considered stem thickness and rigidity; and leaf scoring considered leaf size, color, and overall physiological condition.

Morpho-phenological traits under field conditions

Morpho-phenological traits were recorded monthly from June to September under field conditions. Plant height was measured from the soil surface to the apical tip of the main stem. The numbers of fruiting branches, squares (flower buds), flowers, and bolls per plant were determined by direct counting at each observation stage. At the final growth stage, the numbers of fully opened and half-opened bolls were also recorded.

Cotton yield

Seed cotton yield was determined at harvest maturity from each treatment plot and expressed as $\text{kg}\cdot\text{hm}^{-2}$. Yield data were used for subsequent statistical analysis.

Fiber quality analysis (HVI method)

Fiber quality parameters were analyzed using the High Volume Instrument (HVI) system (Uster Technologies, Switzerland) at the Tashkent Cotton Fiber Testing Laboratory. Parameters measured included fiber length (mm),

uniformity index (%), micronaire value, fiber strength ($\text{cN}\cdot\text{tex}^{-1}$), and elongation (%). Fiber samples were conditioned for 24 h at $(21 \pm 1)^\circ\text{C}$ and $(65 \pm 2)\%$ relative humidity in accordance with ASTM D5867-12 (2020). Measurements were conducted in triplicate, and mean values were used for statistical analysis.

Statistical analysis

Data on seed germination, enzyme activities (POD, CAT, SOD, and PAL), proline and flavonoid contents, seedling resistance to pest damage, morphological traits, fiber quality parameters, and yield were analyzed using GraphPad Prism software (version 8.0.1, GraphPad Software, San Diego, California, USA). Differences among treatments were evaluated by one-way analysis of variance (ANOVA). When significant differences were detected, mean values were separated using the least significant difference (LSD) post hoc test at $P < 0.05$. All data are presented as the arithmetic mean $\pm$ SE ($n = 3$).

Results

Impact of preparations on the early development of cotton seedlings in laboratory conditions

The effects of Aminosid-Aton, Aminosid-Silicon, and Bionitrogen on seed germination and early seedling growth of the cotton cultivar Bukhara-8 are presented in Table 2. In the control treatment, seedlings showed poor growth, with plant height of 13–14 cm, root length of 6–7 cm, weak root systems, thin stems, and delicate cotyledons.

All tested preparations significantly improved early seedling growth compared with the control. Aminosid-Aton treatment increased seedling height to 22–24 cm and root length to 12–14 cm, along with enhanced stem strength and leaf development. Bionitrogen treatment resulted in further enhancement, producing seedlings 24–25 cm in height with root lengths of 14–15 cm and well-developed root systems. The most pronounced

Table 2 Influence of preparations on early seedling growth of cotton

Treatment	Plant height/cm	Root length/cm	Root system	Stem characteristics	Leaf characteristics
Control	13–14	6–7	Weak, poorly developed, sparse root hairs *1–2	Adequately formed *2–3	Cotyledons very thin and delicate *1
Aminosid-Aton	22–24	12–14	Well developed, but few root hairs *3	Strong and healthy *3	Well-developed, robust *3
Aminosid-Silicon	33–34	17–18	Highly developed, firm, with abundant root hairs *4–5	Straight, thick *4	Broad, well-veined, firm and healthy appearance *4
Bionitrogen	24–25	14–15	Well-developed, firm, densely covered with root hairs *4	Short, upright, thick *3–4	Broadly expanded, well-veined *4

Values are presented as approximate ranges. Root system, stem strength, and leaf characteristics were assessed using a five-point qualitative scale (1 = very weak, 5 = excellent), with scores indicated by asterisks

response was observed in seedlings treated with Aminosid-Silicon, which reached heights of 33–34 cm and developed roots 17–18 cm in length. These seedlings exhibited abundant root hairs, firm stems, and well-developed leaves. Relative to the control, Aminosid-Silicon treatment resulted in an approximately 2.5-fold increase in shoot height and a nearly 2.7-fold increase in root length. All tested preparations enhanced early seedling vigor under laboratory conditions, with the silicon-based treatment showing the greatest improvements in morphological traits.

Effects of seed treatments on cotton germination under saline field conditions

Field experiments demonstrated that all seed treatments improved cotton germination under saline soil conditions (Fig. 1). Germination rates in seeds treated with Aminosid-Aton, Aminosid-Silicon, and Bionitrogen were consistently higher than in the control throughout the observation period. At the final assessment, the control treatment exhibited a germination rate of 78.3%, which was lower than that observed in all treated variants. Germination in Aminosid-Aton- and Bionitrogen-treated seeds reached 88.8% and 93.1%, corresponding to increases of approximately 13.4% and 18.9%, respectively, relative to the control. The highest germination rate was observed in seeds treated with Aminosid-Silicon, reaching 96.3%, which represents an increase of approximately 23.0% compared with the control.

Seedlings derived from Aminosid-Silicon-treated seeds demonstrated more advanced early growth compared with those from the control and other treatments under saline field conditions (Fig. 2). Compared with the untreated control and other treatments, Aminosid-Silicon-treated seedlings exhibited larger cotyledons, thicker stems, and more vigorous early development, indicating improved establishment under stress conditions.

Effects of preparations on antioxidant enzyme activities in cotton seedlings

Antioxidant enzyme activities in cotton seedlings differed significantly among treatments, with all treated variants exhibiting higher enzyme activities than the control (Fig. 3). In control seedlings, POD activity (in protein) was $134.96 \text{ U}\cdot\text{mg}^{-1}$. This increased to $141.65 \text{ U}\cdot\text{mg}^{-1}$ in response to the Aminosid-Aton treatment, representing an increase of 5.0% relative to the control. In the Bionitrogen treatment, POD activity (in protein) increased to $147.87 \text{ U}\cdot\text{mg}^{-1}$ (9.6% higher than the control), whereas the highest POD activity was observed in the Aminosid-Silicon treatment at $152.01 \text{ U}\cdot\text{mg}^{-1}$ (12.6% higher than the control). A similar trend was observed for CAT, with activity (in protein) increasing from $81.78 \text{ U}\cdot\text{mg}^{-1}$ in the control to 94.08, 99.01, and $103.21 \text{ U}\cdot\text{mg}^{-1}$ in seedlings treated with Aminosid-Aton, Bionitrogen, and Aminosid-Silicon, respectively.

The CAT activities of three treatments correspond to increases of 15.0%, 21.1%, and 26.2%, respectively,

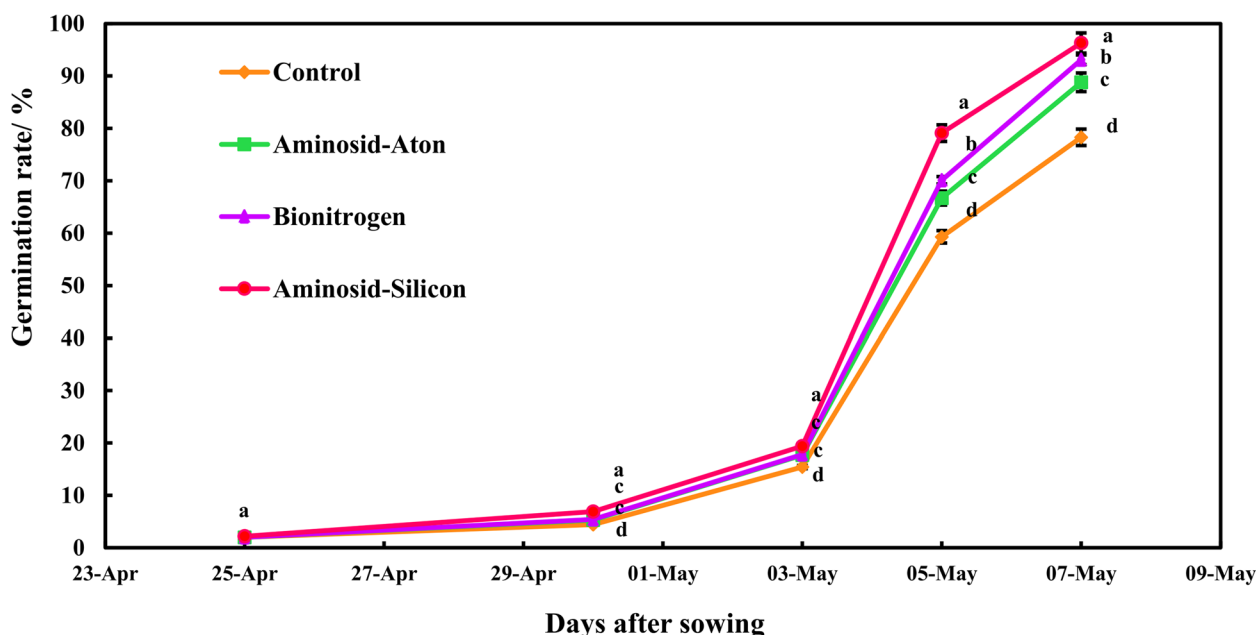


Fig. 1 Influence of seed priming preparations on the germination rate of cotton seeds under field conditions. Values represent mean $\pm$ SE ($n = 3$). Different lowercase letters indicate significant differences among treatments according to the LSD test at $P < 0.05$

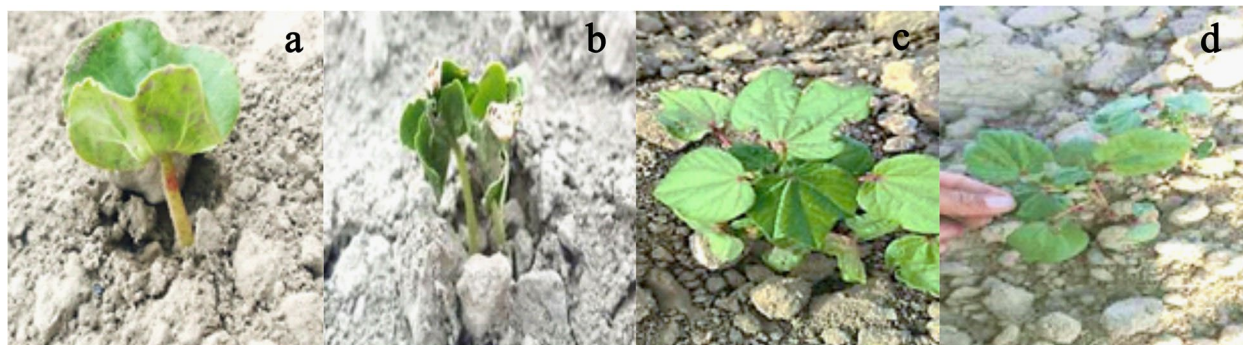


Fig. 2 Early development of cotton seedlings under different treatments in arid saline soil. Representative field photographs showing early cotton seedling development under different seed priming treatments in saline field conditions: (a) Control, (b) Aminosid-Aton, (c) Aminosid-Silicon, and (d) Bionitrogen

relative to the control. PAL activity also responded strongly to the applied preparations. PAL activity (in protein) increased from $128.0 \text{ U}\cdot\text{mg}^{-1}$ in control seedlings to $207.2 \text{ U}\cdot\text{mg}^{-1}$ under the Aminosid-Aton treatment and to $211.3 \text{ U}\cdot\text{mg}^{-1}$ under the Bionitrogen treatment, corresponding to increases of 61.9% and 65.1% compared with the control. The highest PAL activity was observed under the Aminosid-Silicon treatment, reaching $233.6 \text{ U}\cdot\text{mg}^{-1}$, which represented an increase of 82.5% relative to the control. The increase in PAL activity is consistent with the observed accumulation of flavonoids under the treatments. Overall, enzyme activity consistently followed the trend: Aminosid-Silicon > Bionitrogen > Aminosid-Aton > control treatment, indicating a strong activation of antioxidant defense systems, particularly under silicon treatment.

Effects of preparations on non-enzymatic metabolites in cotton seedlings

The contents of non-enzymatic metabolites, including flavonoids and proline, were significantly affected by the treatments (Fig. 4). Flavonoid content in control seedlings (fresh weight) was $133.12 \text{ mg}\cdot\text{g}^{-1}$. Treatment with Aminosid-Aton and Bionitrogen increased flavonoid content (fresh weight) to 143.12 and $143.22 \text{ mg}\cdot\text{g}^{-1}$, corresponding to increases of 7.5% and 7.6%, respectively, compared with the control. The highest flavonoid content was recorded in seedlings treated with Aminosid-Silicon, reaching $153.69 \text{ mg}\cdot\text{g}^{-1}$ fresh weight, which represents an increase of 15.4% relative to the control. Proline accumulation also increased in all treated variants. Proline content in control seedlings (fresh weight) was $112.3 \text{ }\mu\text{g}\cdot\text{g}^{-1}$, whereas values increased to 122.3 , 136.5 , and $144.7 \text{ }\mu\text{g}\cdot\text{g}^{-1}$ in the Aminosid-Aton, Bionitrogen, and Aminosid-Silicon treatments, respectively. The highest proline accumulation observed under Aminosid-Silicon treatment corresponded to an increase of 28.8% compared with the control. These results indicate that

all treatments enhanced osmoprotectant and secondary metabolite accumulation, with Aminosid-Silicon showing the strongest effect.

Effects of preparations on cotton seedlings under insect pest infestation

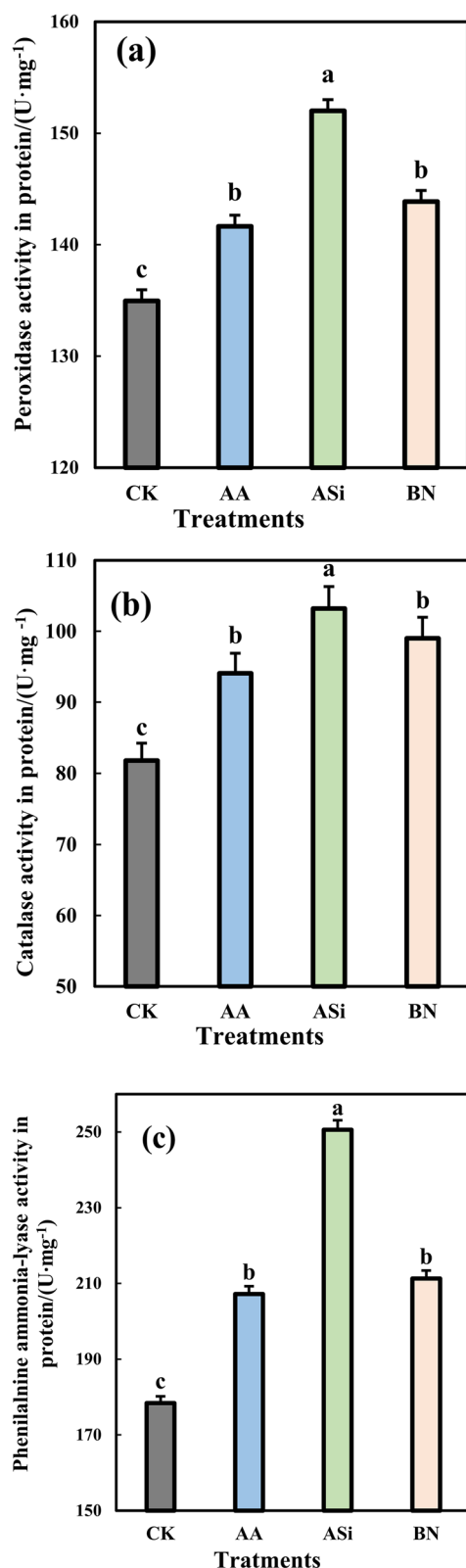
Under natural field conditions, all treatments reduced insect pest infestation compared with the control, with a particular focus on thrips (*Thysanoptera*), whiteflies (*Aleyrodinae*), spider mites (*Tetranychus urticae*), and cotton bollworms (*Helicoverpa armigera*) (Table 3).

The untreated control showed the highest levels of pest infestation. Mean population densities reached 57.9 thrips, 53.1 whiteflies, 58.3 spider mites, and 54.9 bollworms per 1 000 plants, resulting in an infestation of 22.4% of seedlings. Application of Bionitrogen reduced the total infestation level to 14.5%, while a comparable reduction to 14.3% was observed following treatment with Aminosid-Aton. The lowest pest populations were observed in seedlings treated with the Aminosid-Silicon preparation. In this treatment, mean densities declined to 31.2 thrips, 29.2 whiteflies, 31.5 spider mites, and 24.9 bollworms per 1 000 plants. As a result, total infestation was reduced to 11.7%. These results demonstrate that Aminosid-Silicon effectively enhances resistance to pest infestation under field conditions.

Effect of preparations on morpho-phenological traits of cotton under field conditions

Monthly assessments conducted from June to September were used to evaluate the effects of preparations on the morpho-phenological development of cotton plants under field conditions (Table 4).

Differences between treated plants and the control were evident from the early growth stages. In June, all preparations promoted vegetative growth relative to the



◀ **Fig. 3** Effect of different preparations on peroxidase (a), catalase (b), and phenylalanine ammonia-lyase (c) activities in cotton at the two-leaf stage under salinity stress. Values represent mean $\pm$ SE ($n=3$). Different lowercase letters indicate significant differences among treatments according to the LSD test at $P < 0.05$. CK – control, AA – Aminosid-Aton, ASi – Aminosid-Silicon, BN – Bionitrogen

control, with the most pronounced response observed in Aminosid-Silicon-treated plants. These plants reached a height of 32.9 cm and developed 7.3 fruiting branches and 6.7 squares (flower buds), whereas control plants attained a height of 26.3 cm with 5.0 fruiting branches and 2.2 squares (flower buds). By July, treatment-related differences became more distinct. Aminosid-Silicon-treated plants reached a height of 71.0 cm, formed 11.5 fruiting branches, and produced 18.2 squares (flower buds).

In addition, early reproductive structures were observed in Aminosid-Silicon-treated plants, including 0.6 flowers and 3.7 bolls per plant, exceeding the corresponding values recorded in the control. During August, treated plants continued to exhibit higher values for both vegetative and reproductive traits compared with the control. The Aminosid-Silicon treatment resulted in the tallest plants (95.4 cm), the highest number of fruiting branches (16.5), and increased boll formation (9.9 bolls per plant). At the final assessment in September, treated plants showed enhanced boll development and maturation. Plants treated with Aminosid-Silicon produced an average of 12.5 bolls per plant, including 2.89 fully opened and 2.3 half-opened bolls, with a mean boll weight of 3.3 g. In contrast, control plants produced an average of 9.1 bolls per plant, including 2.09 open and 1.0 half-opened boll, and had a lower mean boll weight (2.8 g). Overall, all treatments improved morpho-phenological traits, with Aminosid-Silicon consistently providing the greatest enhancement across all growth stages.

Effect of Aminosid-Silicon on superoxide dismutase activity and fiber development in cotton

The effect of Aminosid-Silicon on SOD activity in cotton ovule integuments was assessed at 20, 30, and 40 days after ovule development (Fig. 5). At 20 days, SOD activity (in protein) in Aminosid-Silicon-treated plants was $54.18 \text{ U} \cdot \text{mg}^{-1}$, which was 14.8% higher than the control value of $47.21 \text{ U} \cdot \text{mg}^{-1}$. At 30 days, SOD activity in treated plants reached a maximum of $86.13 \text{ U} \cdot \text{mg}^{-1}$, exceeding the control level of $78.31 \text{ U} \cdot \text{mg}^{-1}$ by 10.0%. By 40 days, SOD activity declined markedly in both treatments, with values of $3.43 \text{ U} \cdot \text{mg}^{-1}$ in Aminosid-Silicon-treated plants and $14.75 \text{ U} \cdot \text{mg}^{-1}$ in the control. Morphological observations indicated that fiber initiation occurred at an earlier developmental stage in Aminosid-Silicon-treated plants,

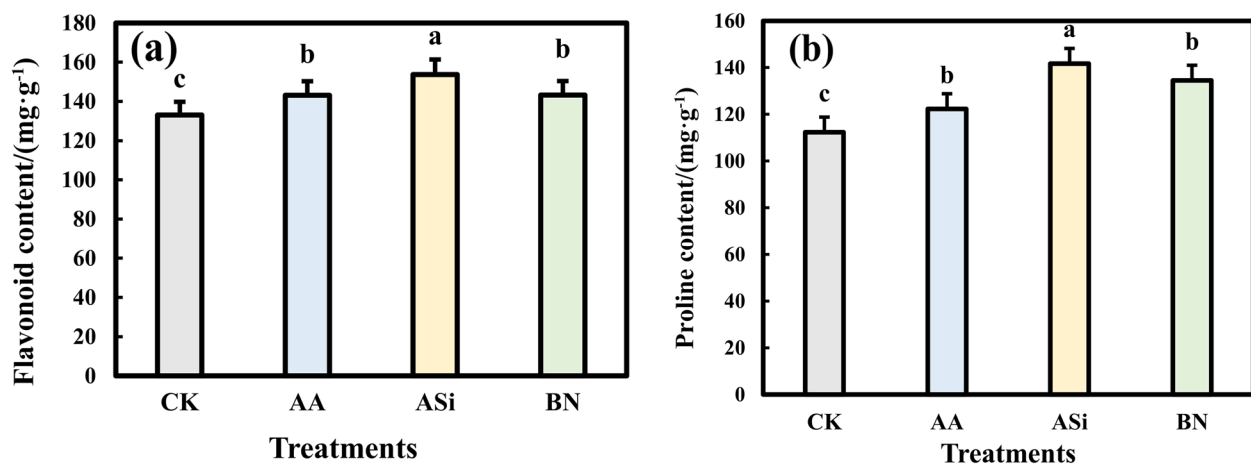


Fig. 4 Effect of preparations on flavonoid (a) and proline (b) contents in cotton at the two-leaf stage under salinity stress. Values represent mean $\pm$ SE ($n=3$). Different letters above the bars indicate significant differences among treatments at $P < 0.05$. CK – control, AA – Aminosid-Aton, ASi – Aminosid-Silicon, BN – Bionitrogen

Table 3 Effects of preparations on cotton seedling resistance to pest damage

Preparations	Numbers of different pest species per 1 000 plants affected					Proportion of infested and healthy plants/%	
	<i>Thysanoptera</i>	<i>Aleyrodinae</i> (subfamily)	<i>Tetranychus urticae</i>	<i>Helicoverpa armigera</i>	Average number	Infested plants	Healthy plants
Control	57.9 $\pm$ 0.08 a	53.1 $\pm$ 0.03 a	58.3 $\pm$ 0.04 a	54.9 $\pm$ 0.08 a	2242 a	22.4 a	77.6 c
Aminosid-Aton	38.4 $\pm$ 0.03 b	36.6 $\pm$ 0.02 b	33.8 $\pm$ 0.04 b	34.4 $\pm$ 0.03 b	1430 b	14.3 b	85.7 b
Aminosid-Silicon	31.2 $\pm$ 0.04 d	29.2 $\pm$ 0.01 d	31.5 $\pm$ 0.01 d	24.9 $\pm$ 0.08 d	1170 d	11.7 c	88.3 a
Bionitrogen	37.7 $\pm$ 0.03 c	35.6 $\pm$ 0.01 c	36.4 $\pm$ 0.04 c	35.3 $\pm$ 0.03 c	1450 c	14.5 b	85.5 b

Pest infestation is expressed as the number of individuals per 1 000 plants for each pest species. Values represent the mean $\pm$ SE of three independent replicates ($n=3$). Different lowercase letters within the same column indicate significant differences among treatments based on one-way ANOVA followed by the LSD post hoc test at $P < 0.05$.

corresponding to an advancement of approximately 10 days compared with the control.

Histochemical analysis of developing cotton fibers in 20 and 40-day-old bolls demonstrated that the application of Aminosid-Silicon resulted in a progressive decrease in superoxide anion accumulation as fiber development advanced (Fig. 6).

This reduction in superoxide levels indicates a mitigation of oxidative stress during fiber maturation and is associated with the thickening of the secondary cell wall, a characteristic feature of fiber maturation. Based on histochemical observations, cotton fibers treated with Aminosid-Silicon reached physiological maturity approximately 10 days earlier than those in the control treatment.

Effect of Aminosid-Silicon on cotton fiber quality parameters

The effect of Aminosid-Silicon on cotton fiber quality was evaluated using High Volume Instrument (HVI) analysis (Table 5). Treatment with Aminosid-Silicon

resulted in statistically significant differences in several key fiber quality parameters compared with the control at $P < 0.05$. The spinning consistency index (SCI) increased from 129 to 137, indicating improved spinning stability. Fiber length increased accordingly, with the upper half mean length (UHML) rising from 26.7 to 28.4 mm. Fiber strength increased from 30.1 to 32.4 cN·tex⁻¹, while the short fiber index (SFI) declined from 9.1% to 7.5%, reflecting a reduction in undesirable short fibers. Improvements were also observed in fiber optical properties, as brightness (R_d) increased from 78.6% to 80.8%, whereas yellowness (+ b) decreased from 7.1 to 6.2. In addition, fiber maturity and elongation differed significantly among treatments at $P < 0.05$, with the highest values observed under the Aminosid-Silicon treatment. Collectively, these results demonstrate that Aminosid-Silicon treatment enhanced the structural, physical, and optical characteristics of cotton fiber, which is associated with improved spinning performance.

Table 4 Effects of preparations on growth- and yield-related traits of cotton during the growing season

Month	Parameter	Control	Aminosid-Aton	Bionitrogen	Aminosid-Silicon
June	Plant height/cm	26.3±0.03 d	29.3±0.11 c	30.1±0.06 b	32.9±0.09 a
	Fruiting branch No.	5.0±0.08 d	6.4±0.11 b	6.1±0.03 c	7.3±0.02 a
	Square (flower bud) No.	2.2±0.11 d	4.1±0.12 b	4.0±0.11 c	6.7±0.01 a
July	Total height/cm	64.0±0.02 c	68.0±0.02 b	68.0±0.21 b	71.0±0.11 a
	Fruiting branch No.	10.3±0.04 c	10.8±0.03 b	10.8±0.09 b	11.5±0.13 a
	Square (flower bud) No.	13.4±0.05 c	16.8±0.11 b	16.9±0.01 b	18.2±0.09 a
	Flower No.	0.3±0.21 c	0.4±0.10 b	0.4±0.04 b	0.6±0.03 a
	Boll No.	2.3±0.30 d	3.1±0.08 c	3.6±0.02 b	3.7±0.07 a
August	Plant height/cm	88.1±0.06 c	93.5±0.02 b	93.6±0.11 b	95.4±0.11 a
	Fruiting branch No.	13.8±0.12 c	15.6±0.09 b	15.5±0.02 b	16.5±0.01 a
	Square (flower bud) No.	10.3±0.22 d	11.4±0.04 c	11.6±0.09 b	12.1±0.10 a
	Flower No.	1.7±0.10 d	2.0±0.05 c	2.3±0.05 b	2.4±0.03 a
	Boll No.	7.2±0.20 d	9.4±0.11 c	9.7±0.05 b	9.9±0.07 a
September	Boll No.	9.1±0.10 d	11.2±0.22 c	11.5±0.11 b	12.5±0.11 a
	Open boll No.	2.09±0.04 d	2.72±0.02 c	2.85±0.06 b	2.89±0.23 a
	Half-open boll No.	1.0±0.03 d	2.1±0.01 c	2.2±0.01 b	2.3±0.12 a
	Boll weight/g	2.8±0.01 c	3.1±0.11 b	3.1±0.12 b	3.3±0.13 a

Values represent the mean±SE of three independent replicates ($n=3$). Different lowercase letters within the same row indicate significant differences between treatments based on one-way ANOVA followed by the LSD post hoc test at $P<0.05$

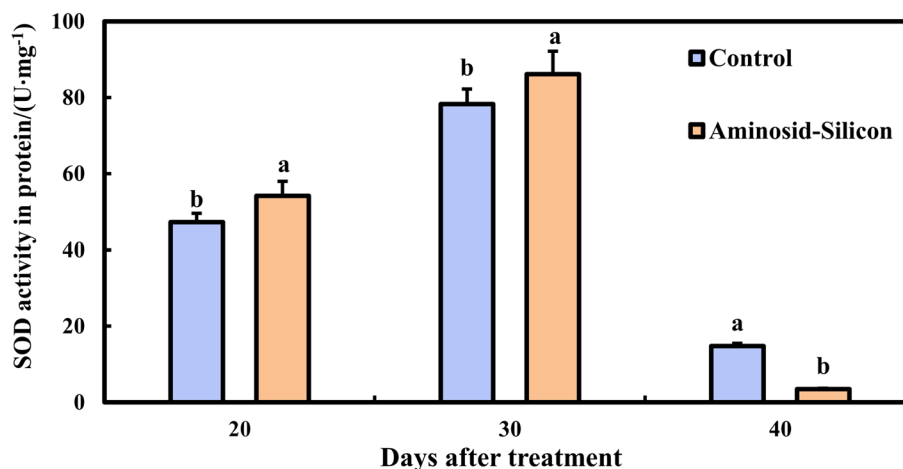


Fig. 5 Effect of aminosid-silicon on superoxide dismutase activity in cotton ovule integuments during 20–40 days of development. Values represent mean ± SE ($n=3$). Different lowercase letters at the same time point indicate significant differences between treatments according to the LSD test at $P<0.05$

Effects of preparations on seed cotton yield under stress conditions

Seed cotton yield varied significantly among treatments under saline field conditions (Fig. 7). The lowest yield was recorded in the untreated control, reaching 3 830 kg·hm⁻². Application of all tested preparations resulted in a marked increase in seed cotton yield compared with the control.

Treatment with Aminosid-Aton increased yield to 4 380 kg·hm⁻², while Bionitrogen application resulted in a yield of 4 260 kg·hm⁻². The highest seed cotton yield was obtained with silicon-based treatment, reaching 4 620 kg·hm⁻², which corresponds to an increase of approximately 20.6% relative to the control. Cotton productivity significantly increased by the tested preparations with the highest yield improvement observed under the silicon-based treatment.

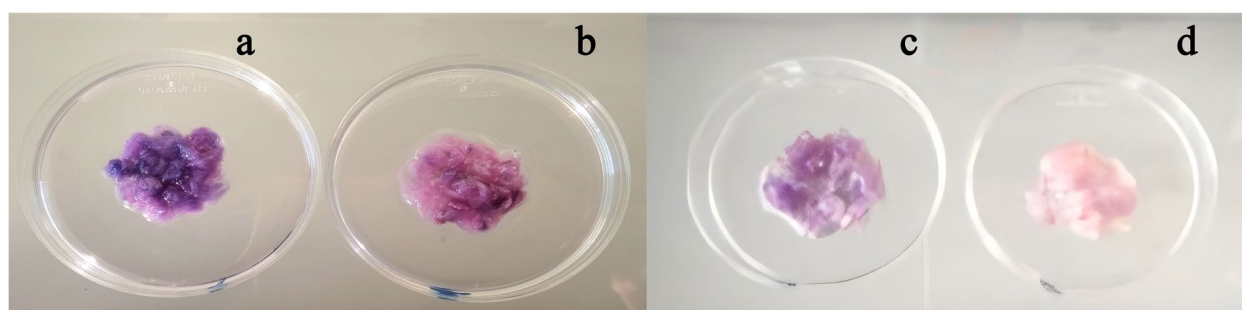


Fig. 6 Effect of Aminosid-Silicon on SOD activity and superoxide accumulation during early cotton fiber development. Representative histochemical staining images showing superoxide anion radical accumulation in cotton ovule integuments. Darker blue staining indicates higher superoxide anion radical accumulation. Panels (a) Control and (b) Aminosid-Silicon represent samples at 20 days of development, whereas panels (c) control and (d) Aminosid-Silicon represent samples at 40 days of development

Table 5 Effect of aminosid-silicon on fiber quality parameters of Bukhara-8 cotton

Fiber quality parameters	Control	Aminosid-Silicon
Spinning consistency index	129.0±0.01 b	137.0±0.01 a
Micronaire	4.10±0.09 b	4.50±0.011 a
Maturity ratio	0.87±0.012 a	0.88±0.011 a
Upper half mean length/mm	26.7±0.02 b	28.4±0.01 a
Uniformity index/%	83.60±0.04 a	83.50±0.09 a
Short fiber index/%	9.10±0.011 a	7.50±0.013 b
Fiber strength/(cN·tex ⁻¹)	30.10±0.1 b	32.40±0.1 a
Fiber elongation/%	5.90±0.03 b	6.30±0.07 a
Reflectance/%	78.60±0.02 b	80.81±0.01 a
Yellowness/+ b	7.10±0.014 a	6.18±0.022 b
Color grade	41.20±0.08 a	41.10±0.03 a

Values represent the mean ± SE of three independent replicates ($n=3$). Different lowercase letters within the same row indicate significant differences between treatments based on one-way ANOVA followed by the LSD post hoc test at $P<0.05$. Values within each row are ranked from highest (a) to lowest (b)

Discussion

This study demonstrates that silicon-based preparations, particularly Aminosid-Silicon, enhance the physiological performance, fiber quality, and productivity of cotton under both laboratory and field conditions. These findings are consistent with growing evidence indicating that, although silicon is not classified as an essential element, it functions as a beneficial nutrient by enhancing plant tolerance to environmental stress and improving overall agronomic performance (Marxen et al. 2016).

The positive effects of Aminosid-Silicon on seed germination and seedling establishment were accompanied by enhanced root system development, increased cotyledon expansion, and hypocotyl strengthening. Comparable observations have been reported in other crops; for example, Tripathi et al. (2021) and Ayed et al. (2022) demonstrated that silicon application promoted both shoot and root growth, thereby supporting early morpho-physiological processes essential for uniform

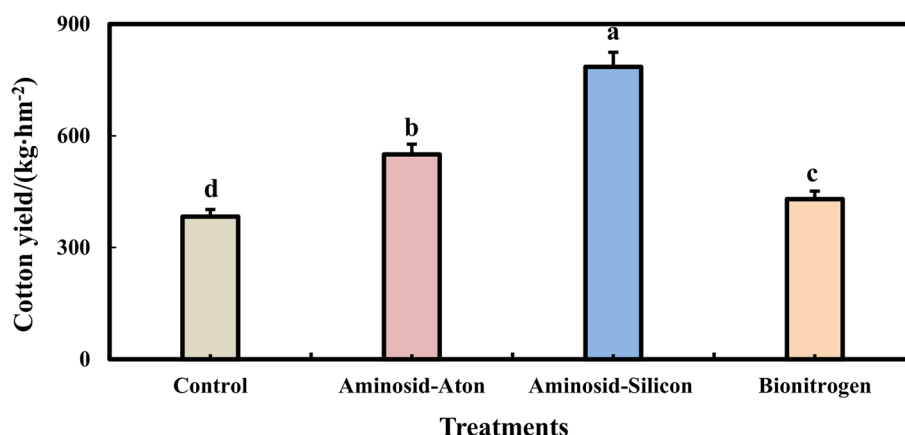


Fig. 7 Effect of preparations on seed cotton yield under stress conditions. Values represent mean ± SE ($n=3$). Different lowercase letters above bars indicate significant differences among treatments at $P<0.05$ (LSD test)

stand establishment. These early-stage benefits are likely attributable to silicon's dual role as both a structural component reinforcing tissue integrity and a signaling regulator modulating cellular activities. In particular, the observed increases in root length and root hair density underscore silicon's critical role in enhancing water and nutrient uptake efficiency, a function that is especially important in stress-prone environments.

At the biochemical level, the enhancement of germination and seedling vigor under silicon treatment appears to be closely linked to the activation of both enzymatic and non-enzymatic antioxidant defense systems. The elevated activities of catalase, peroxidase, superoxide dismutase, and phenylalanine ammonia-lyase indicate an enhanced capacity for ROS scavenging, thereby protecting cellular structures and maintaining metabolic stability (Hasanuzzaman et al. 2022; Shomali et al. 2022). Moreover, the observed accumulation of proline and flavonoids further underscores silicon's role in osmotic adjustment, antioxidant buffering, and stress mitigation. Previous studies have demonstrated that silicon stimulates the phenylpropanoid pathway and enhances the activity of pyrroline-5-carboxylate synthetase (P5CS), thereby promoting proline biosynthesis, maintaining osmotic balance, and stabilizing cellular proteins under drought and salinity conditions (Maghsoudi et al. 2018; Mao et al. 2025). Taken together, these mechanisms indicate that silicon acts as a priming agent that activates defense systems at early developmental stages, thereby promoting germination and subsequent growth under suboptimal conditions.

Based on the integrated physiological, biochemical, and agronomic responses observed in this study, a mechanistic framework can be proposed to explain how Aminosid-Silicon enhances cotton tolerance to salinity stress. Silicon application appears to first improve early seedling establishment by stimulating root elongation and root hair development, thereby facilitating water uptake and reducing the initial osmotic shock associated with saline conditions. Concurrently, silicon strengthens cellular antioxidant capacity through the coordinated activation of enzymatic defenses (superoxide dismutase, catalase, peroxidase, and phenylalanine ammonia-lyase) and non-enzymatic components, including flavonoids and proline. This integrated antioxidant and osmoprotective response likely limits oxidative damage to membranes and metabolic enzymes, thereby maintaining cellular integrity under salt-induced stress. At the structural level, silicon deposition within cell walls may enhance tissue rigidity and membrane stability, reduce ion leakage, and improve ionic homeostasis under saline conditions.

During later developmental stages, these protective effects extend to fiber elongation and maturation, where balanced redox regulation and cell wall plasticity support

improvements in fiber length and uniformity. Collectively, these interconnected processes suggest that Aminosid-Silicon acts as a priming agent by integrating root-mediated water acquisition, redox homeostasis, osmotic regulation, and structural reinforcement to enhance overall plant resilience under salinity stress. In addition to mitigating abiotic stress, silicon also confers protective effects against biotic challenges. Silica deposition within epidermal tissues enhances structural rigidity, forming physical barriers that limit insect feeding, while silicon-mediated activation of salicylic acid and jasmonic acid signaling pathways contributes to systemic resistance induction (Reynolds et al. 2016; Goswami et al. 2022; Denarié et al. 2025).

The present findings confirm that silicon not only reinforces the structural integrity of cotton seedlings but also biochemically primes defense systems, thereby enhancing their overall stress resilience. Beyond its effects during early development, silicon markedly influenced fiber elongation and maturation. The elevated activity of oxidative enzymes, including superoxide dismutase, during fiber development likely contributed to a more balanced regulation between cell wall lignification and elasticity, ultimately resulting in longer and more uniform fiber (Stephenie et al. 2020).

The observed improvements in fiber quality properties, including UHML, SCI, and reduced SFI values, emphasize the agronomic and industrial relevance of silicon application, particularly in enhancing spinning performance and lint quality. Furthermore, the yield-promoting effect of Aminosid-Silicon aligns with previous reports in maize and other crops under drought conditions, where silicon was shown to enhance metabolic stability, water-use efficiency, and overall productivity (Sirisuntornlak et al. 2021). Compared with the control, Aminosid-Aton increased seed cotton yield by approximately 14.4%; Bionitrogen, by 11.2%; and Aminosid-Silicon, by 20.6%, highlighting the superior agronomic and economic performance of silicon-based treatments. In the study, the observed yield enhancement is likely the cumulative outcome of improved germination, enhanced stress resilience, strengthened enzymatic protection, and improved fiber quality. This integrated response underscores the potential of silicon-enriched biostimulants as a promising component of sustainable cotton production systems under climate change-induced stress conditions.

Overall, these findings provide strong evidence that silicon exerts a multifaceted and system-level role in plant growth and stress resilience. By promoting early vigor, reinforcing enzymatic and structural defense systems, improving fiber development, and stabilizing yield performance, Aminosid-Silicon represents a practical tool for increasing the sustainability and efficiency of cotton cultivation. Future research across multi-environment field conditions

is essential to validate these benefits on a broader agro-economic scale and further elucidate the molecular mechanisms underlying silicon-mediated improvements. In particular, future studies should focus on the regulation of stress-responsive genes, signaling pathways, and the synthesis of defense-related proteins to achieve a more precise understanding of silicon-driven stress adaptation.

Conclusion

This study provides evidence that the silicon-based preparation Aminosit-Silicon significantly improves the physiological, biochemical, and morphological performance of cotton under salinity stress. Treated seedlings exhibited enhanced germination rates, increased seedling vigor, and improved survival under stress conditions, which were associated with elevated activity of key antioxidant enzymes and higher accumulation of osmoprotectants such as proline and flavonoids. Enhanced metabolic regulation effectively reduced oxidative damage and reinforced structural and biochemical defenses against major cotton pests. The treatment further improved morpho-phenological traits, fiber quality parameters, and ultimately yield, confirming the role of silicon in strengthening plant resilience. These findings substantiate the hypothesis that silicon supplementation alleviates both abiotic and biotic stresses while supporting sustainable cotton production and promoting adaptive agronomic practices in degraded and arid environments.

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Authors' contributions

Mamasolieva M and Saidova M conducted biochemical analyses, prepared figures, and contributed to drafting the manuscript. Makhkamova D performed statistical analyses and interpreted agronomic data. Yadgarov A supported the study with material and technical resources, including the provision of necessary reagents and instruments. Yangiboyev A conducted field trials and monitored agronomic performance. Babaev B and Gafurova L developed the research concept and experimental design. Babaeva Z contributed to advanced statistical analysis. Hudonazarov I supervised laboratory analyses and reagent preparation. Yusupov B provided expertise in plant physiology and supported field observations. Tursinbaev M coordinated technical and institutional support. All authors read and approved the final manuscript.

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Data availability

The datasets supporting the conclusions of this article are included within the article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

Author Yusupov B is affiliated with Rasayana LLC (Aminosit brand), which provided the preparations for research purposes only. Neither the author nor the company had any role in the experimental design, data collection, data analysis, interpretation of results, or manuscript preparation. All other authors declare that they have no competing interests.

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