

Effects of Different Application Rates of Silicon Fertilizer on Growth, Yield, and Fiber Quality Traits of Cotton (*Gossypium hirsutum* L.)

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Posted Date: April 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9075038/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Journal of Cotton Research on July 24th, 2026. See the published version at <https://doi.org/10.1186/s42397-026-00278-w>.

1 **Effects of Different Application Rates of Silicon Fertilizer on Growth, Yield, and Fiber Quality**
2 **Traits of Cotton (*Gossypium hirsutum* L.)**

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Abstract

Cotton (*Gossypium hirsutum* L.) is used as cash crops and widely grows in Xinjiang but has some major stress such as drought and salinization which severely effect cotton yield and its quality. Silicon nutrients are not considered as essential nutrients, but it effectively alleviates environmental stress and how silicon effects against stress are still unknown. Our study aims to investigate effect of silicon different concentrations on stresses and cotton production in adverse conditions of Xinjiang, revealing the mechanism and appropriate concentration rate by foliar methods to provide proper guidance for the enhancement of cotton in Xinjiang region. A complete randomize block design was used with four different silicon treatments rate with the available silicon content by 0%, 10%, 30% and 50%, called as control (CK, no silicon application), low silicon application rate treatment (L, 0.25g Si L⁻¹), medium silicon application (M, 0.50g Si L⁻¹) and high silicon application rate treatment (H, 1.00g Si L⁻¹). During both years of cotton growing agronomic traits, dry matter accumulation and distribution, leaf physiological indexes (MDA, Pro, POD, SOD, CAT, GR), yield components and fiber quality were systematically measured. Silicon application rate effects on cotton growth and yield were explored through comprehensive analysis of multiple indexes. Silicon foliar application significantly enhances cotton agronomic traits which are responsible for cotton vigor, growth and yield. Silicon nutrients have beneficial effects on proline content, antioxidant activities (superoxide dismutase, peroxidase, catalase, malondialdehyde) and glutathione content reductase in cotton leaves ($P < 0.05$). By improving cotton agronomic traits and leaves physiological indexes silicon especially medium and high concentration significantly cotton biomass. Silicon foliar application enhances the cotton yield and its components but there is no significant difference between silicon concentrations with ($P < 0.05$). Silicon fertilizer enhances the agronomic traits, biomass, proline and other antioxidants activities which directly affect cotton yield against adverse conditions in Xinjiang. According to our study two years results silicon high (H, 1.00g Si L⁻¹) can be used as recommended dosage for cotton physiology and yield enhancement.

Keywords: Silicon, cotton, antioxidant, biomass, production, fiber quality

1 INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is the most widely cultivated fiber crop and importantly used by textile industry and its seeds contain proteins and oil which can be used as food and bioenergy approximately 2.5% of the Globe (El-Ashmouny et al., 2026; Liu et al., 2019) which provides high income to farmers (Kapeleka et al., 2025). Cotton crop supports around 100 million families all over the world (Khosro et al., 2025), contributing over US\$500 billion in annual economic value (Chen et al., 2020). China carries historic and economic cotton values so it deeply integrated in China agricultural and textile culture to support rural livelihoods around major planting areas so today cotton consider as the most strategic cash crop and provide strong foundation to textile and garment industry (Cheng et al., 2024). China produces 25.6% (30 million bales) of global output, with 87% of its cotton originating from the Xinjiang province. Due to differential climatic conditions in Xinjiang such as drought, soil salinization and other abiotic stresses inhibit the photosynthetic efficiency of cotton leaves which ultimately effect cotton production (Mao et al., 2025). To attain sustainable cotton production against stresses, enhancing physiological and chemical performance, it's essential to use available nutrients efficiently for sustainable Xinjiang cotton industry. Among all agronomic practices silicon foliar application has gained a special and considerable attention which can positively alleviate the effect of drought (da Silva Liber Lopes et al., 2023). Si nutrients are the second most abundant nutrients on the Earth's crust but still not considered as essential nutrients for plants but considered as important nutrients. It plays positive effect against drought, salinity pest and disease (Malik et al., 2021). As foliar application plants can absorb in the form of monoclinic acid $[\text{Si}(\text{OH})_4]$, which is very less in amount in soil due to its low solubility (Kupdhoni et al., 2025). Several previous studies stated that silicon nutrients act as bio stimulant, increases plant growth, development level, and stress tolerance by number of metabolic, physiological, chemicals and structural mechanisms (Coskun et al., 2019; Debona et al., 2017). Si strengthen antioxidant enzymes activities, regulate endogenous hormones, activate stress responsive genes, enhances photosynthesis, decrease electrolyte leakage, maintain nutrients, deposits silica in the epidermal cells tissues and increases the membrane stability by cell wall thickening (Saha et al., 2021). Silicon fertilizer effect deferentially on plants species such as rice (*Oryza Sativa*) absorb 10% of Si which cause the enhancement of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Fajardo et al., 2025) and contribute countries sustainability such as Japan and South Korea in rice yields since 1950s, and 1960s respectively. Silicon foliar application has a positive effect on cotton crop production but shows less effect on other

crops such as rice (Hodson et al., 2005). There are some studies which define the internal mechanism of silicon to improve cotton stress resistance, but our study investigates physiological mechanism to influence cotton growth, development and production of cotton crops. Silicon nutrients act as beneficial nutrients which can enhance cotton production and overall crop performance. Silicon foliar application at different (bud, flowering, boll and boll opening) stages improves Si accumulation through leaves, enhances cotton agronomic traits, chlorophyll, antioxidant activities, ultimately enhances biomass and cotton production (de Souza Junior et al., 2020; Ferraz et al., 2014). Silicon nutrients show beneficial effects on cotton growth and cause the development of fiber and its quality (Li et al., 2024) which shows its importance in cotton growth and production. Previous studies stated the beneficial effect of silicon on cotton physiology, yet limited studies which state the direct link between silicon fertilizer and nutrients efficiency. But silicon instructions with macronutrients like N, P, K, calcium (Ca), magnesium (Mg), and sodium (Na) are still unexplored in cotton crops. Our hypothesis states that silicon foliar application with different concentrations have beneficial role in increasing cotton growth, biomass, antioxidant and overall cotton production by improving physiological, chemical and nutrients uptake efficiency performance. Our study undertakes to investigate the Si supplementation with different concentrations to improve cotton. Our findings are expected to explore and give support to silicon foliar application with optimum level for cotton production.

2 MATERIALS AND METHODS

2.1 Study site

The field experiment was implemented at the Changji Comprehensive Station of Chinese Academy of Agricultural Sciences (44°05'N, 87°31'E) in northwest of China. The region is subjected to a typical temperate continental arid climate. The long-term mean annual precipitation is 190 mm, and it is obviously higher in summer. The mean annual temperature is 6.8 °C, with monthly means ranging from -15.6°C in January to 24.5 °C in July. The accumulative precipitation during the cotton growing seasons was 250-300 mm and 200-250 mm in 2024 and 2025, respectively (Fig. 1).

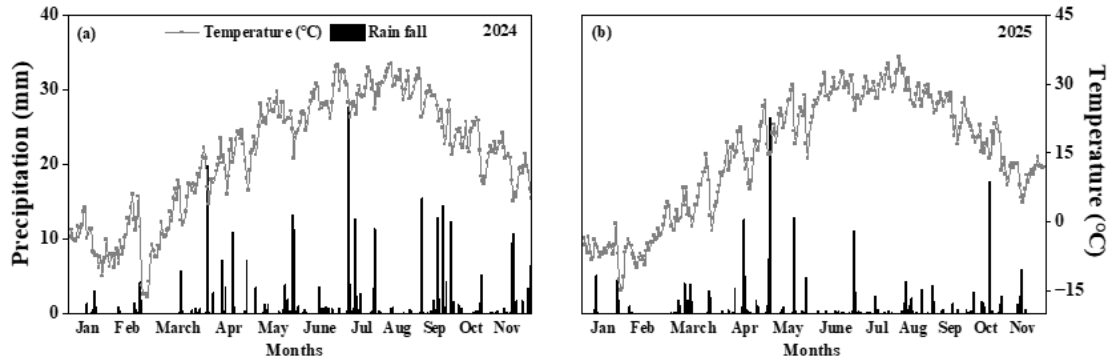


Fig. 1 Daily average temperature and rainfall during the cotton growing stages of whole years (January–November) for field experiment (2024–2025).

This experiment was conducted at the Changji Comprehensive Experimental Base of the Western Agricultural Center, Chinese Academy of Agricultural Sciences (44°26'N, 87°32'E), with an altitude of 470 m and an average annual temperature of 7 °C, which falls under a continental climate. The soil texture of the experimental field was sandy loam with a moderate and uniform basic fertility. The basic physiochemical properties of the tested soil samples in the 0–20 cm layer were as follows, organic matter 9.48 g·kg⁻¹, total nitrogen 0.52 g·kg⁻¹, available phosphorus 25.84 mg·kg⁻¹, available potassium 493.67 mg·kg⁻¹, and available silicon 157.38 mg·kg⁻¹.

The soil in this region is classified as a gray descry soil, with sand of 51%, silt of 32%, clay of 17%, organic matter of 9.48 g kg⁻¹, total nitrogen of 0.52 g·kg⁻¹, available phosphorus 25.84 mg·kg⁻¹, available potassium 493.67 mg·kg⁻¹, available silicon 157.38 mg·kg⁻¹. bulk density of 1.45 g·cm⁻³, and pH of 8.0 in the 0–20 cm soil layer at the beginning of experiment in 2024.

2.2 Experimental design

We used a complete random block design with four treatments, including the control (CK, 0.00 g Si L⁻¹), low Si concentration (L, 0.25 g Si L⁻¹), medium Si concentration (M, 0.50 g Si L⁻¹), and high Si concentration (H, 1.00 g Si L⁻¹). Each treatment had three replicates, and the plot size was 9.12 m × 9 m. Cotton (cultivar Zhongmian 113) was sown in mid-April each year and the integrated management of water and fertilizer was used throughout the cotton growing seasons. We adopted a cultivation mode of “one film, three tapes, and six rows”, where cotton was planted in wide and narrow rows (66 cm + 10 cm) and the plant spacing was 9 ~ 11 cm and 10 + 66 cm spacing between each row. Each drip irrigation tape (patch type) with emitter spacing of 30 cm and flow rate of 20 L h⁻¹ was placed in the middle of the narrow row. The width of plastic film used in this study was 2.28 m. To enhance germination and seedling establishment, all plots were drip-irrigated with water of 30 mm after sowing. Each plot received a total

of 225 mm of irrigation water from mid-June to late August, with frequencies of 6 times and irrigation cycle of 7–10 days. During the seedling, bud, flowering and boll stages, Si fertilizer (SiO_2 , 50%) was sprayed onto the leaves of cotton according to the specified dosage for each treatment. Besides, nitrogen, 35 kg of urea (N 46%), 10 kg of potassium dihydrogen phosphate (P_2O_5 52%, K_2O 34%) were applied with dripping water per mu during growth period were dissolved in fertilizer tanks were fertigated 6 times through the drip irrigation system. Other field practices were the same as those used by local farmers.

2.3 Sampling and measurements

2.3.1 Determination of agronomic traits

To ensure the accuracy of integrity and trackability of results that silicon effects on plant height, randomly six plants were selected from each treatment and growth indicator were measured at different (seedling, bud, flowering, boll and boll opening stage) stages (Santos et al., 2020). Plant height was measured with the help of measuring tape from the cotyledon node to the top of the cotton growth point (Rabeh et al., 2023). Stem diameter was measured with the help of digital vernier caliper to get precise measurements of stem thickness under different concentrations at different stages. Mosses per plant were counted manually and recorded in the excel sheet for statistical analysis (Laane, 2018). For main stem leaves we count same six selected plants from each plot that were used to clearly differentiate from lateral branches to avoid error. Main stem leaves counted from first fully expanded leaf at base of main stem to top growth of cotton plant. All data was recorded in detail with accurate integrity of the experiment which consists of standard requirements of agronomic traits in literature.

2.3.2 Biomass

Cotton plants samples for dry matter allocation at different (seedling, bud, flowering, boll and boll opening stage) stages. Six plants were taken from each silicon concentrated respective block, cut into root, stem, leaves and bud, placed in an oven at 105 °C for 30 min, and dried at 80 °C for constant weight. Samples were weighed according to organs (root, stem, leaves, bud) data were recorded accurately for each silicon treatment block across both years by using the electric balance (Ren et al., 2023). Total dry matter accumulation and distribution ration of each part of plant were (dry weight of part / total weight × 100%) calculated. After taking dry weight each plant part and Kjeldahl method used to process the sample for subsequent nutrient content.

2.3.3 SPAD value

Ground data mainly included the SPAD values of cotton crops. SPAD value measuring instrument was SPAD502 Plus (produced by Minolta, Tokyo, Japan), and for measuring cotton SPAD value five-point sampling method used. To ensure to get accurate results we measured cotton four leaves on top, and three leaves after topping. Each leave was measure five times and the average was taken as SPAD value for each plot cotton plants (Wang et al., 2024). We repeat this process at five different (seedling, bud, flowering, boll and boll opening stage) stages of cotton plant to see the effect of silicon different concentrations

2.3.4 Leaf physiological indicators

Five leaves samples were collected at SS (seedling stage), BuS (bud stage), FS (flowering stage), BoS (boll stage), BOS (boll opening stage). Complete developed and fully extended leaves are usually fourth from the top of each plant. Samples were immediately placed into liquid nitrogen to stop the activity before being transferred into the storage area of laboratory. Later these leaves were transferred into – 80 °C refrigerator to determine enzyme activity (SOD, CAT, POD, GR) and MDA and proline (Ali et al., 2023).

Our two years study investigates the effect of silicon concentration (CK, low, medium, high) on leaf physiological indices. At different (bud, flowering, boll and boll opening) stages in both years leaves were collected from respective plants plot. After collecting leaves were wrapped and labeled with tinfoil to avoid light induces changes and snap frozen in liquid nitrogen and transferred to -80 °C for storage. Which provides reliable basis for subsequent determination of proline (Pro) content, superoxide dismutase (SOD), peroxidase (POD), catalase (CAT) activities and malondialdehyde (MDA) content.

Microplate reader (FlexA-200) used to detect absorbance value of leaves physiological indices ensuring high accuracy and reproducibility of results. SOD, POD, CAT activities and Pro content were consistently conducted using the special assay kits by Beijing Solar bioscience and technology co., Ltd, by operating the procedures in accordance with the kit instructions to maintain uniformity and standardization of experimental operations.

MDA content investigated by Thio barbituric acid colorimetric method by using same experimental protocol. Weight 0.05 g of frozen leaf sample, add 1 mL of trichloroacetic acid (TCA), grind to homogenate to fully extract MDA. Homogenate centrifuged at 8000 g for 10 min at 4 °C to separate supernatant. Take 0.5 mL of supernatant, add equal volume of 0.5% TBA solution, conduct temperature reaction in boiling water bath for 15 min, then rapidly cool in ice bath to terminate reaction. Absorbance values at wavelength of 450 nm, 532 nm and 600 nm were measured respectively and MDA content was calculated according to absorbance values. Data was collected accurately for each treatment and growth stage in both years, laying a foundation for subsequent analysis of changes of leaf physiological indices and long-term effects of silicon foliar application.

2.3.5 Cotton yield and its components

At boll opening stage 6.67 m² area was randomly established in each block. For harvest density observation total number of plants and bolls per plant were counted within the selected sample area. Healthy plants were selected from each block and boll were calculated by fruit branch position such as 30 bolls from upper part, 30 bolls from lower part and 40 bolls from middle part, total of 100 boll of cotton plants. Total seed cotton weighed for the average calculation of boll weight. After ginning process, lint cotton weight was weighted to get lint percentage. By using these calculated values theoretical seed cotton yield and theoretical lint cotton yield was calculated from each block of research.

2.3.6 Fiber quality determination

After ginning fiber samples were sent to Cotton Fiber Testing Center of the Cotton Research Institute, Chinese Academy of Agricultural Sciences (CRI, CAAS) for the determination of quality indicators such as average length of upper leaf, neatness index, breaking strength and micron value.

2.3.6 Data Analysis

Microsoft Excel was used for data collection and basic preliminary calculations. All collected data presented as the mean $\pm$ standard error (SE) and were analyzed by sing IBM statistics software, Duncan's multiple range test was performed to examine significant differences ($P < 0.05$) among treatment means

after controlling for multiple comparisons were determined from a least significant difference (LSD) test. and Origin for graph presentation following one way analysis of variance (ANOVA).

3 RESULTS

3.1 Effect of silicon foliar application on agronomic traits

The two-factor variance analysis (Table 1) showed that the main effects of year (Y), fertility period (S) and treatment (T) on the high cotton strain, thick stem, number of fruit branches and number of main stem leaves were significant ($P < 0.001$). The interaction between year and fertility period ($Y \times S$) was also significant ($P < 0.001$), while the interaction among year and treatment ($Y \times T$), fertility period and treatment ($S \times T$) and the three ($Y \times S \times T$) were not significant ($S > 0.05$). As can be seen from (fig 2 a-h), the increases and variances of each indicator in 2024 are significantly greater than in 2025, such as the peak of the spike in boll stage (BoS) in 2024, and the highest and smallest increase in the late belly period in 2025. In growth and development dynamics, the height, stem diameter, mosses number per plants and number of main stem leaves continued to grow from seedling stage (SS) to boll stage (BoS) in 2024, and the overall growth was stable and low in 2025. In terms of treatment effect, CK (control) had the lowest, low treatment was significantly higher than CK but lower than medium and high but these treatments show sufficient effects without significant differences. In the two-year trial, low, medium and high silicon treatment in the first-year increased plant height by 5.8%, 14.5% and 12.4% respectively (fig. a), stem diameter by 12.5%, 19.4% and 14.2% respectively (fig. c), and mosses per fruit branch by 8.77%, 20.8% and 15.5% respectively (fig. e). In the second year, the plant height increased by 3.11%, 7.14%, 7.04% (fig. b), stem diameter increased by 6.2%, 14.3%, 10.06% respectively (fig. d), mosses per fruit branch increased by 11.3%, 10.4%, 12% respectively (fig. h), and the number of main stem leaves also increased at the same time (fig. g-h). The overall promotion effect was higher in the first year than in the second year, and the increase in medium silicon treatment was the most prominent.

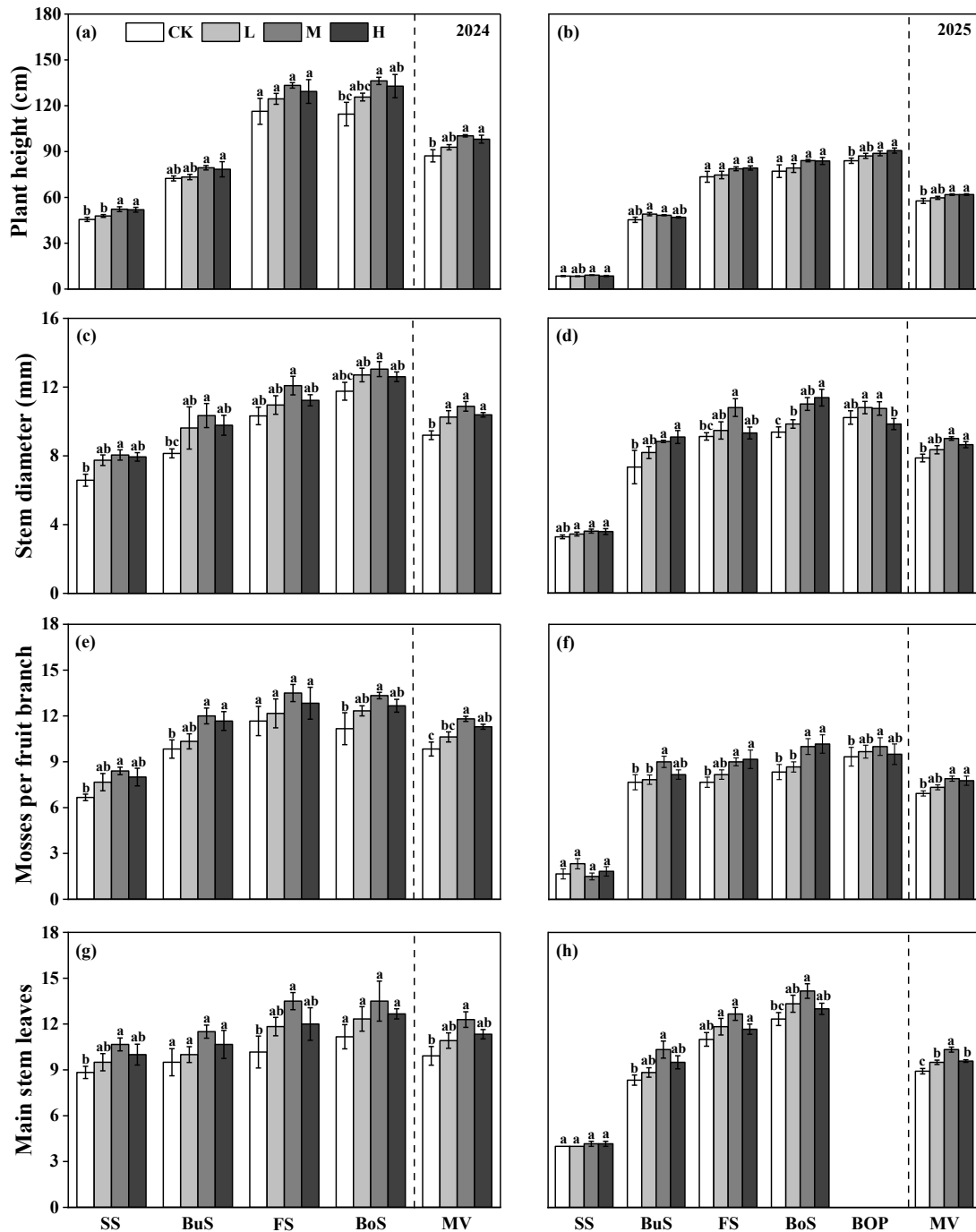


Fig. 2 Effects of Si on plant height, stem diameter, mosses per plant and main stem leaves. CK represents the foliar application of 0 mg L⁻¹. L, M, and H represent the foliar application of 0.25g Si L⁻¹, 0.50g Si L⁻¹, and 1.00g Si L⁻¹ respectively SS (seedling stage), BuS (bud stage), FS (flowering stage), BoS (boll stage), BOP (boll opening stage) and MV (mean value). Similar lowercase letters indicate no significant differences between different treatments ($P < 0.05$).

Table 1 Two-way ANOVA(P-values) of the effects of different growth stages (S) and treatments (T) on plant height, stem diameter, number of fruiting branches, and main stem leaves of cotton in two years (Y) of research.

Effect	Plant height	Stem diameter	Mosses per	Main stem
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	(cm)	(mm)	fruit	leaves
Y	<0.001	<0.001	<0.001	<0.001
S	<0.001	<0.001	<0.001	<0.001
T	<0.001	<0.001	<0.001	<0.001
Y × S	<0.001	<0.001	<0.001	<0.001
Y × T	0.113	0.777	0.602	0.365
S × T	0.239	0.141	0.111	0.416
Y × S × T	0.915	0.787	0.993	0.968

Data are presented as mean values, values followed by different lowercase letters indicate significance at $P < 0.05$, indicates significance at 0.1% probability level, indicates significance at 1% probability level, indicates significance at 5% probability level. Y: Years; S: Stages; T: Treatments.

3.2 Biomass

Growth stage (S) had a highly significant effect ($P < 0.001$) on all cotton biomass traits, while year (Y) significantly influenced root and bud dry weight ($P < 0.001$), but treatment (T) showed no significant effect. Significant interactions were observed for ($Y \times S$) across all biomass parameters ($P < 0.001$) and ($T \times S$) for bud weight and total plant biomass ($P < 0.05$), with no significant three-way interaction ($Y \times T \times S$). During the experiment, moderate and high silicon application rates significantly increased dry matter accumulation in vegetative organs (18.48%–20.76%), (12.01–14.27%), reproductive organs (22.58%–27.92%), (12.51%–14.39%) in first and second growing season respectively. Furthermore, total dry matter accumulation under high silicon application was significantly higher than under moderate silicon application ($P < 0.05$, Fig 3).

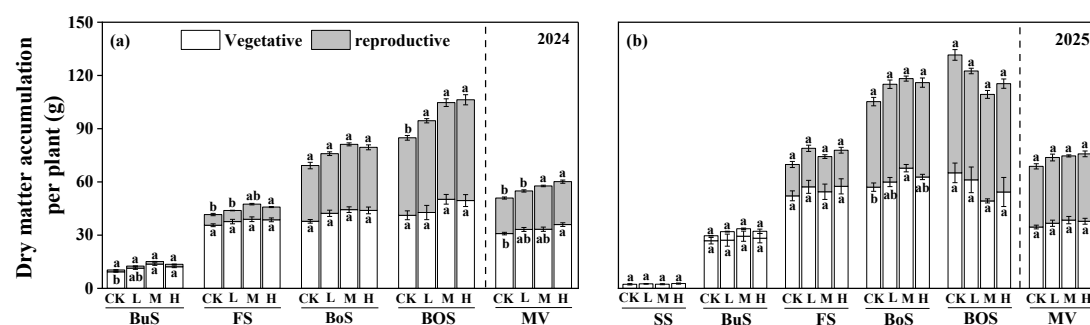


Fig. 3 Dry matter accumulates in vegetative and reproductive organs of cotton. CK, L, M and H represent the proportion of silicon fertilizer applied at different stages. The small letters in the figure indicate that there were significant differences in dry matter among different silicon concentrations ($P < 0.05$).

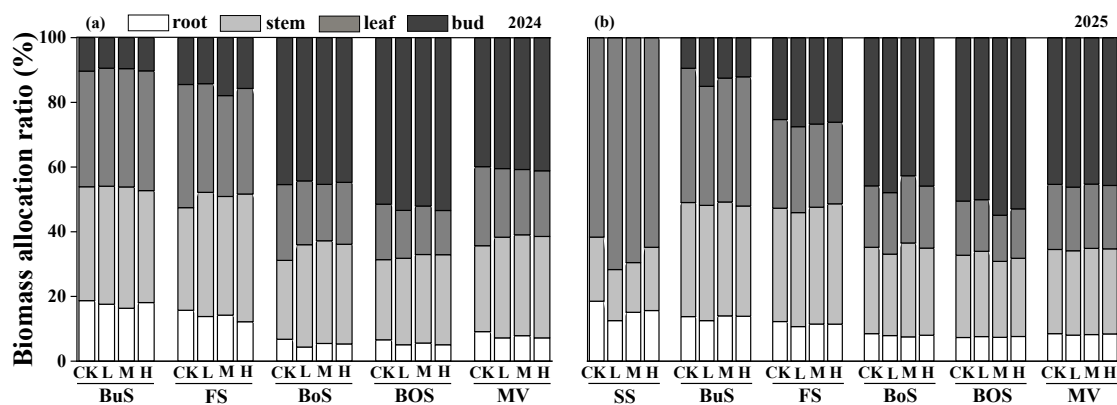


Fig. 4 Effects of different treatments on the dry matter distribution ratio of cotton at different growth stages

Table. 2 Two-way ANOVA(P-values) of the effects of different growth stages (S) and treatments (T) on root dry weight, stem dry weight, leaf dry weight, bud dry weight, and overall plant biomass weight of cotton in two years (Y) of research

Effect	Root weight (g)	Stem weight (g)	Leaf weight (g)	Bud weight (g)	Plant biomass (g)
Y	<0.001	0.808	0.12	<0.001	0.126
T	0.727	0.099	0.924	0.051	0.143
S	<0.001	<0.001	<0.001	<0.001	<0.001
Y × T	0.623	0.469	0.850	0.086	0.495
Y × S	<0.001	<0.001	<0.001	<0.001	<0.001
T × S	0.946	0.323	0.427	0.006	0.011
Y × T × S	0.990	0.994	0.995	0.694	0.996

3.2 SPAD value

Different silicon treatments had no significant effect on cotton chlorophyll content, although the high silicon treatment produced a slight increase (Fig 5). In first year low, medium and high treatments enhanced chlorophyll by 0.74%, 1.34%, and 1.64% respectively. In second year, the enhancements were 0.76%, 1.06%, and 2.01% by low, medium and high silicon treatments respectively.

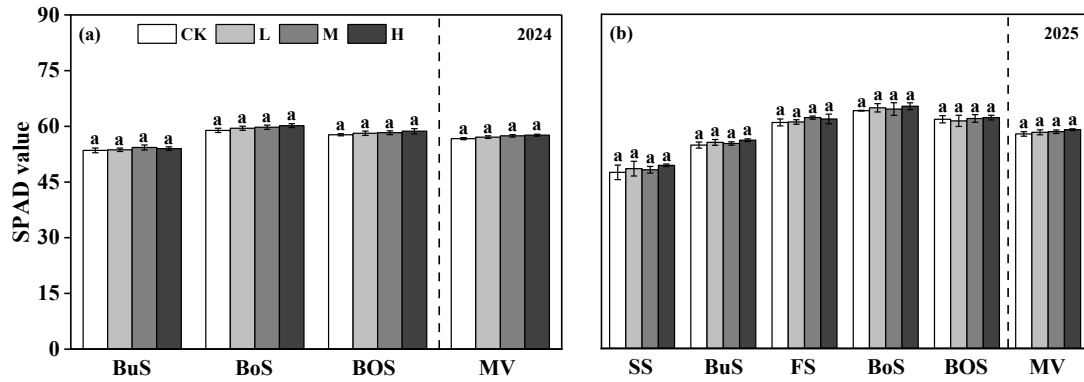


Fig. 5 Dynamics on SPAD value accumulation of cotton with different silicon concentration at different stages.

3.3 Leaf physiological indicators

Silicon treatments effectively mitigate oxidative damage by significantly decreasing malondialdehyde (MDA) content in cotton leaves which are directly associated with lipid peroxidation. Medium and high Si treatments significantly decrease MDA accumulation to protect cell membrane integrity and increase stress tolerance in both years of research trial (fig. 6).

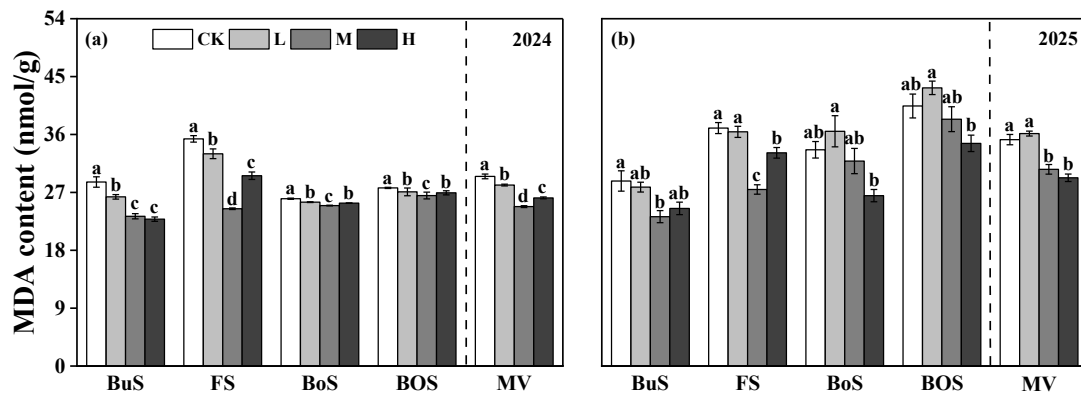


Fig. 6 Effects of different silicon application levels on MDA content and antioxidant-related indices of cotton at different stages.

Silicon treatments significantly enhance Pro content in cotton leaves. Compared with CK proline content increased 9.44%, 16.22%, 13.30% first year (fig 7a) and 6.71%, 9% and 11.02% (fig 7b) with low, medium and high silicon treatments respectively. Proline content was high with medium and high silicon treatments.

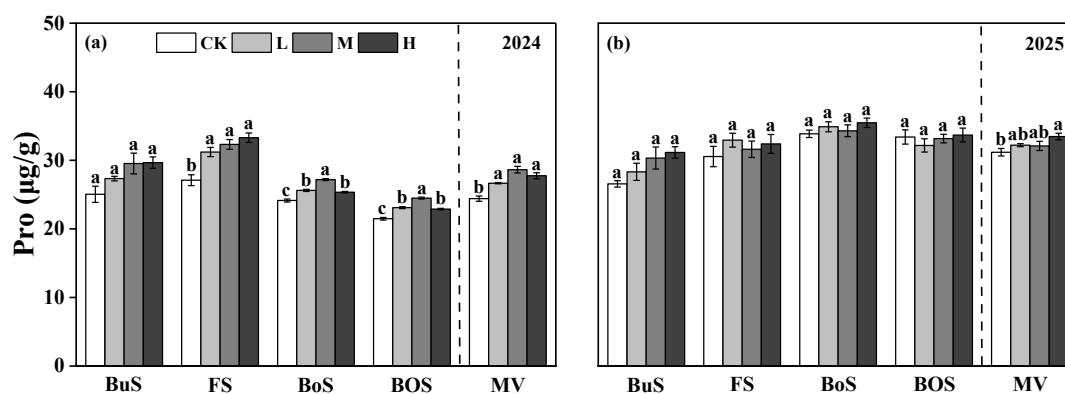


Fig. 7 Effects of different silicon application levels on MDA content and antioxidant-related indices of cotton

Results from our two-year field experiment (2024-2025) demonstrated that silicon foliar treatments significantly enhance antioxidant enzymes including guaiacol peroxidase (POD) in cotton crops. Medium treatment markedly increased POD activities in both years of research in cotton and effectively scavenging reactive oxygen species, reduces hydrogen peroxide (H_2O_2) accumulation. Silicon high treatment increases superoxide dismutase (SOD) activity in cotton leaves. Compared with control (CK) silicon high treatment enhanced SOD activity by 9.45% in 2024 and 17.91% in 2025, effectively scavenging reactive oxygen species, stabilize cell membrane integrity and improve drought stress. With same tread silicon high treatment increases catalase (CAT) activity in cotton. CAT activity monitored at four key stages (seedling, bug, flowering, boll and boll opening) in both years to capture dynamic changes. The results showed high treatment elevated CAT activity by 24.02% and 37.85% both years respectively. Which helps cotton reduce membrane lipid peroxidation and maintain photosynthesis. Silicon medium treatment gets the charge to enhance glutathione reductase (GR) activities in cotton leaves. Compared with control (CK), medium silicon treatment increases leaf GR activities by 22.45%, 14.82% both years of research to maintain high ratio of reduced glutathione (GSH) to oxidized glutathione (GSSG), accelerated ROS scavenging and AsA-GSH cycle. All these antioxidants help cotton plants to support against drought stress and puts effective roll-on cotton growth and production.

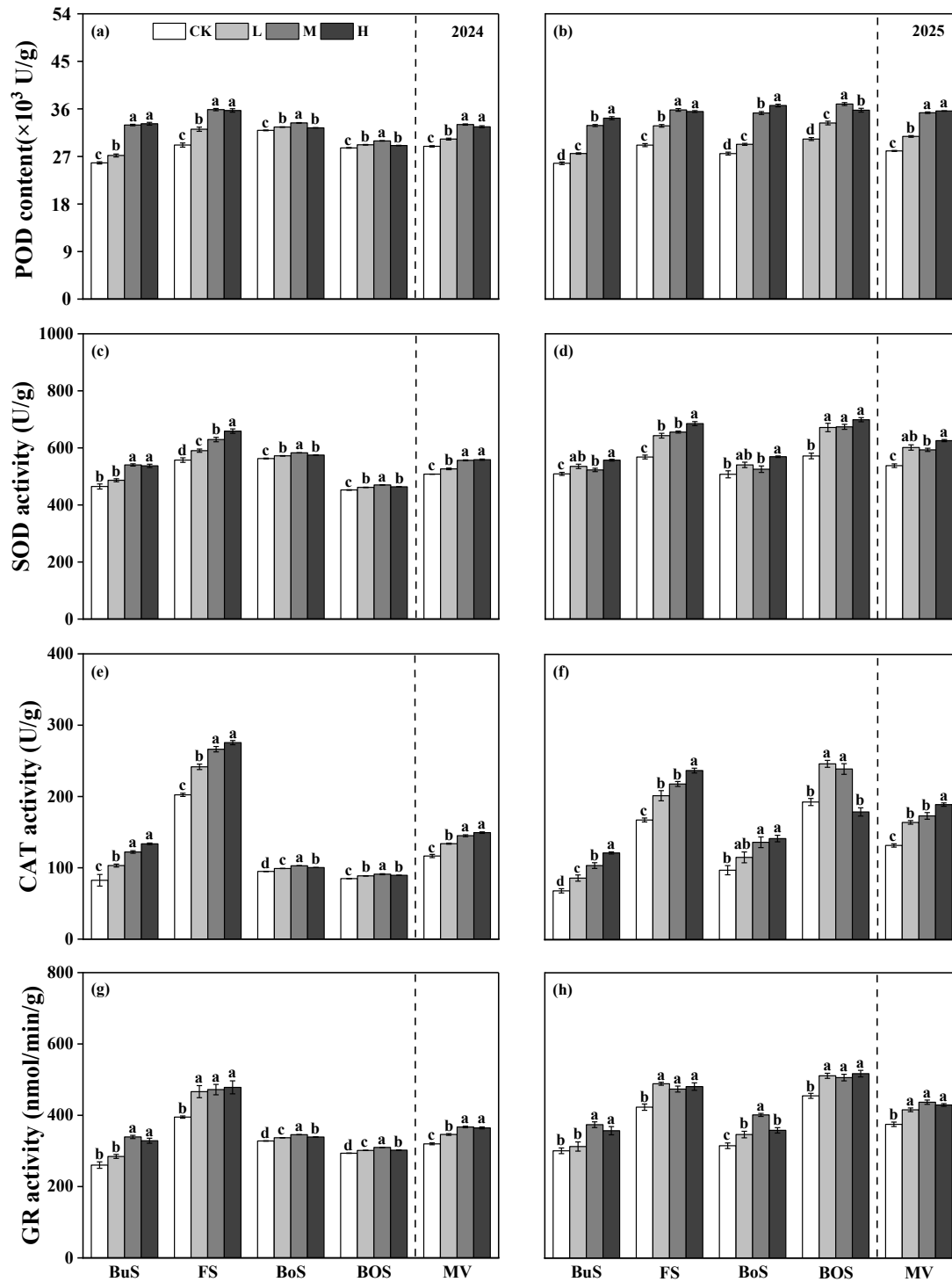


Fig. 8 Effects of different silicon application levels on POD, SOD, CAT and GR content and antioxidant-related indices of cotton

3.4 Effect of foliar application of silicon fertilizer on cotton yield and its components

The two-factor variance analysis (Table 3) showed that the interaction between year and treatment ($Y \times T$) influenced cotton overall production. The main effect of year (Y) on harvest density, boll number per plant, seed cotton yield, and lint cotton yield was significant ($P < 0.05$), and highly significant on single boll weight ($P < 0.001$), but had no significant effect on lint percentage ($P > 0.05$). The main effect of

treatment (T) on single boll weight was extremely significant ($P < 0.001$) but no significant effect on other indices ($P > 0.05$). Seed cotton yield enhances with medium and high silicon treatments 4% to 5%, and about 2% increased with low treatment. In terms of lint cotton yield, it followed the same trend and in first research season, medium and high treatments enhanced lint cotton yield by 6% to 7% compared with CK, but in second growing season, enhancement was about 3%. In two years, research trial, low, medium and high treatments in the first-year enhanced seed cotton yield by 2%, 4% and 5% respectively, lint cotton yield was increased by 6% and 7% with medium and high treatments. In the second year, medium and high concentration treatments also enhanced seed cotton yield by 4% and 5% respectively and by about 2% compared with low level treatment. The overall effect of medium and high treatments on cotton yield was higher in the first year than in the second year, and the medium and high concentration treatments performed best without significant difference in yield promotion.

Table 2 Effects of different silicon application levels on harvest density, yield components and lint yield of cotton.

	Treatments	Harvest density (10 ⁴ /hm ²)	Boll per plant	Single boll weight (g)	Lint percentage (%)	Seed cotton yield (kg/hm ²)	Lint cotton yield (kg/hm ²)
2024	CK	23.00±0.97a	6.66±0.21a	4.57±0.03b	46.02±0.92a	6997±239a	3217±80a
	L	23.95±0.99a	5.97±0.24a	4.75±0.09b	46.77±0.52a	6776±119a	3170±82a
	M	22.75±0.13a	6.20±0.22a	5.20±0.12a	47.10±1.66a	7326±196a	3457±216a
	H	23.05±0.27a	5.89±0.15a	5.36±0.05a	47.26±0.47a	7276±213a	3439±108a
2025	CK	24.80±0.58a	5.85±0.06a	5.14±0.04a	47.38±0.76a	7461±182a	3535±115a
	L	24.85±0.44a	5.98±0.36a	5.22±0.06a	47.11±0.81a	7743±247a	3651±167a
	M	24.10±0.78a	5.81±0.07a	5.24±0.06a	47.48±1.09a	7337±97a	3484±89a
	H	24.05±0.18a	6.02±0.21a	5.26±0.03a	47.79±0.51a	7605±214a	3633±81a

Table 3 Two-way ANOVA(P-values) of the effects of different growth stages (S) and treatments (T) on harvest density, boll number per plant, single boll weight, lint percentage, seed cotton yield, and lint

326 cotton yield in two years (Y) of research

Effect	Harvest density (10 ⁴ /hm ²)	Boll number per plant	Single boll weight (g)	Lint percentage	Seed cotton yield (kg/hm ²)	Lint cotton yield (kg/hm ²)
Y	0.012	0.094	<0.001	0.332	0.006	0.012
T	0.436	0.465	<0.001	0.813	0.713	0.614
Y × T	0.889	0.148	<0.001	0.938	0.145	0.357

327 Data are presented as mean values, values followed by different lowercase letters indicate significance
 328 at $P < 0.05$, indicates significance at 0.1% probability level, indicates significance at 1% probability level,
 329 indicates significance at 5% probability level. Y: Years; S: Stages; T: Treatments

330 Silicon treatments significantly affected cotton yield but had no significant effects on yield components
 331 such as harvest density, bolls per plant, and lint percentage ($P > 0.05$, Table 3). Compared with the control
 332 (CK), medium treatment significantly increased seed cotton yield by 19.1% and lint cotton yield by
 333 13.6%. Low and high silicon treatments show an increasing trend with no significant differences among
 334 silicon treatments. Silicon treatments had no significant effects on fiber quality indices, including average
 335 length of upper leaf, neatness index, breaking strength, and micronaire value, and all fiber quality
 336 indicators met the standards for high-quality cotton ($p > 0.05$, Table 5).

337 **Table 4** Impacts of silicon application levels on cotton yield parameters, average upper leaf length and
 338 fiber quality indices (neatness, breaking strength, micron value).

	Treatments	Average length of upper leaf	Neatness index %	Breaking strength cN/tex	Macron value
2024	CK	29.67±0.32a	84.83±0.98a	30.13±0.58a	4.50±0.31a
	L	30.00±0.50a	85.40±0.56a	29.50±0.25a	4.80±0.12a
	M	30.83±0.43a	84.13±0.73a	31.23±0.73a	5.23±0.15a
	H	31.23±0.44a	86.27±0.24a	30.97±0.49a	4.47±0.15a
2025	CK	31.50±0.35a	84.67±0.43a	29.40±0.64b	4.57±0.22a
	L	30.83±0.15a	84.77±1.00a	32.37±0.57ab	4.73±0.15a
	M	30.33±0.84a	85.28±0.58a	31.63±1.00ab	5.00±0.31a
	H	31.27±0.52a	84.13±0.38a	33.23±1.01a	5.10±0.21a

339

340

341 **Table 5** Two-way ANOVA(P-values) of the effects of different growth stages (S) and treatments (T) on
 342 average length of upper leaf, neatness index, breaking strength, macron value and stretch of cotton fiber
 343 quality in two years (Y) of research

Effect	Average length of upper leaf	Neatness index %	Breaking strength cN/tex	Macron value
Y	0.124	0.353	0.027	0.511
T	0.346	0.844	0.027	0.088
Y × T	0.123	0.147	0.072	0.229

Data are presented as mean values, values followed by different lowercase letters indicate significance at $P < 0.05$, indicates significance at 0.1% probability level, indicates significance at 1% probability level, indicates significance at 5% probability level. Y: Years; S: Stages; T: Treatments

4 DISCUSSIONS

Drought stress is the major factor which highly affects the quality and yield of cotton in Xinjiang (Lv et al., 2026). It decreases agronomic traits, effect on biomass by inducing lipid peroxidation, chlorophyll in leaves and effects the metabolic valance which directly affect cotton yield (Song et al., 2026). Although silicon is not considered an essential element but has widely beneficial effects on crops to modulate physiological, chemical and morphological mechanisms to increase growth, tolerance and production (Fajardo et al., 2025; Sultan et al., 2026). Silicon foliar application is efficient method for the supplementation of elements to cotton, but soil application has some limitations such as fixation, leaching but as foliar application direct deposition to targeted tissues against drought stress (da Silva Liber Lopes et al., 2023; Niu et al., 2020). High silicon concentration has beneficial effect on all measured parameters where low Si concentration also shows minimal benefits to the CK in both cotton seasons (Wang et al., 2021). Our study investigated that silicon fertilizer can construct a stable stress resistance physiological mechanism by regulating leaf physiological metabolisms. Silicon foliar application reduces the MDA content in cotton leaves, although results were not significant but overall trend was downward which causes the alleviation of lipid peroxidation damage and maintains the cell membrane integrity. Silicon foliar application shows the lowest average content of MDA in both years of research because it increases the plant antioxidant capacity to decrease membrane lipid peroxidation. MDA low levels state low oxidative damage higher cell membrane stability which helps cotton to improve stress resistance and normal physiological mechanisms (Cannea & Padiglia, 2025). Silicon application can decrease lipid peroxidation damage under drought stress and stable the cell membrane for normal functioning of leaf photosynthesis and physiological mechanisms (El-Beltagi et al., 2025). Si fertilizer increases leaf proline (Pro) content ($p < 0.05$), enhances accumulation of osmotic regulatory substances, increases water

retention efficiency and provide tolerance against drought stress which provides a stable environment for leaf physiological proper activities. Silicon fertilizer foliar application has significant effects to activate antioxidant defense system by regulating antioxidant enzymes activities and GR content which clear reactive oxygen species by drought stress and reduce oxidative damage in cotton crops (Shah et al., 2024). Cotton plants show this effect mostly on flowering and at boll opening stages. Silicon enhances SOD, POD, CAT and GR content during flowering stage ($P < 0.05$). POD antioxidants were regulated the most at flowering stage in first season and boll opening stage in second year. SOD, CAT enzymes activities significantly increased by silicon which indicates the regulation of cotton leaf antioxidant system which depends upon silicon application dosage. Seed cotton and lint cotton yield were increased with silicon applications with antioxidant contents ($P < 0.05$). Our study results suggest that appropriate silicon applications can regulate and optimize antioxidant activities which reduce reactive oxygen damage to cotton leaves and provide the stability of leaf physiological metabolism which provide sufficient support for agronomic traits formation and dry matter accumulation. This is considered as key indicator on which silicon fertilizer shows positive effect against drought stress and regulates cotton yield and quality (El-Beltagi et al., 2025).

Regulation of leaf physiological mechanisms can enhance agronomic traits formation, chlorophyll and efficient biomass which is directly responsible for cotton yield and its components by silicon foliar application (Kupdhoni et al., 2025). In our study silicon treatments shows the highest effect on chlorophyll contents because it enhances the cotton plant's ability to capture light from sun with the help of photosynthesis and change into plants energy (Khalequzzaman et al., 2024). This enhancement in photosynthesis contributed to higher biomass and for cotton production (Yu et al., 2024). This enhancement in chlorophyll content with high silicon concentration is likely to increase stress tolerance as reducing oxidative stress which prevents chlorophyll degradation of cotton crops. Higher the chlorophyll, higher photosynthate which support biomass accumulation and reproductive development (Chen et al., 2018). Cotton agronomic traits formation and biomass are directly affected by nutrients and environmental stresses, while cotton plants leaf physiological metabolism determines the developmental quality of agronomic traits and biomass efficiency (Wang et al., 2024). Our study found that agronomic traits and biomass are associated with plant height, stem diameter, moss per plant and main stem leaves. Higher the agronomic traits, higher the biomass and these were at their peak at flowering stage first year and were at peak at boll stage in second growing season with medium silicon application. Different

silicon concentration shows significant differences within the growing stages which highlight that silicon concentration effect on different stages under drought stress on cotton crops (Abbas et al., 2023). Among all the silicon treatments medium concentration shows significant results at with the average of different stages increases in height 12%, 19%, 20%, in first and 7%, 14%, 10% in second season of growth than the control ($p < 0.05$) of plant height, stem diameter and mosses per plant respectively. Cotton this enhancement is considered silicon optimize the leaf physiological metabolism for example cell wall mechanical enhancement, plants structural support and osmotic adjustment enhancement for water use efficiency which directly effect on drought stress. Leaf stability ensures photosynthesis efficiency, chlorophyll content, sufficient nutrients for agronomic traits development which regulate the rhythm vegetative and reproductive cotton growth allowing the plants to maintain good health and avoid premature disturbances due to drought stress. So, improving the agronomic traits the improvement of cotton growth and yield.

Biomass or accumulation and distribution of dry matter, the application of silicon fertilizers reinforced the inherent distribution strategy of cotton to adapt to arid environments (Ren et al., 2023). Medium concentration takes charge and enhances vegetative and reproductive organs of the cotton crop. Average enhancement of the vegetative part of cotton plants with silicon low, medium and higher than CK 10.27%, 20.76 and 18.48% respectively and reproductive organ increases with the percentage of 9.54% with low, 27.92% with medium and 22.58% with high concentration in first season. Second season average vegetative enhancement was 10.03% with low, 12.01% with medium and 14.27% with higher concentration than the control and reproductive part with the total average of 10.22%, 12.51%, 14.39% with low, medium and high concentrations foliar applications ($P < 0.05$). This enhancement is closely related to leaf physiological metabolism as silicon increases photosynthetic performance by optimizing relationship between source and sink which increases the biomass. Medium and high concentration show a significant difference, but low concentration shows very small difference of dry matter accumulation and distribution. These results give basic knowledge of enhancement due to silicon application.

It has shown effect by strengthening the cell wall to increase the quality of fiber by enhancing cellulose and lignin deposition in cotton crops and enhances the economic value of cotton crops (Djikanovic et al., 2025). Improvement due to silicon application under adverse drought conditions in Xinjiang is the main objective of cotton cultivation. In our study, cotton and fiber quality were at its peak with medium application in first season and with high concentration in the second season of growing than the control

or CK ($P < 0.05$). High silicon concentration exhibited the best performance on single boll weight 5.36g first and 5.26g second growing season. Enhancement in the cotton yield is not only effected by a single trait but effected by combined effects such as leaf physiological optimization, agronomic traits, biomass, chlorophyll and antioxidant activities against environmental stresses. There is a significant positive relation between seed cotton yield and yield components such as number of bolls and boll weight (both $P < 0.05$). Effects of silicon fertilizer on the cotton yield components such as boll per plant, boll weight, seed cotton yield and lint percentage directly related to cotton production (Farooq et al., 2013). These findings indicate that number of boll and weight were very important traits to increase cotton production. Silicon fertilizer reduces MDA content, increases Pro content, CAT activity and regulates SOD activities to mitigate drought stress. Silicon enables cotton plants for efficient biomass, provides sufficient nutrients and water for boll development, which ultimately causes the enhancement of cotton overall production of cotton. Silicon has this potential to enhance farmers aiming to maximize yield and fiber production. This shows that excessive silicon concentration always produces the highest cotton production but if it is in excessive form it may interfere with the nutrients uptake and shows potentially imbalance or toxicity (Khan et al., 2021). This evaluates that under the high concentration of silicon optimizing the most beneficial effects on the results, as silicon is beneficial for cotton growth, so it is used at optimal range.

5 CONCLUSIONS

The results showed that foliar applications of silicon with different concentrations (CK, 0.00 g Si L⁻¹), low Si concentration (L, 0.25 g Si L⁻¹), medium Si concentration (M, 0.50 g Si L⁻¹), and high Si concentration (H, 1.00 g Si L⁻¹) helped cotton plants better growth and production during both growing seasons. Additional improvements in cotton antioxidants mechanisms, productivity, and fiber quality were also observed. As a result, these practices can significantly enhance cotton vigor productivity.

ACKNOWLEDGEMENT

We sincerely acknowledge the scientists due to their various contributions to the dataset compiled in this research paper. This research was financially supported by Xinjiang Talent Development Fund Program (XJRC-2025-KJ-YJ-CXPT-037), Natural Science Foundation of Xinjiang Uygur Autonomous Region (2024D01B92), Changji Prefecture Science and Technology Program (2025S02-01), National Pilot Project for Standardization, Natural Science Foundation of Henan (262300421541), the Fundamental Research Funds for Central Public Welfare Research Institutes of the Institute of Cotton Research of the

Chinese Academy of Agricultural Sciences (YSH22404300171, 1610162025027), and Changji Station,
Chinese Agrosystem Long-Term Observation Network (CALTON-CJ) .

CONFLICTS OF INTEREST

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

REFERENCES

- Abbas, A., Sattar, A., Ul-Allah, S., Sher, A., Ijaz, M., Abbas, T., Irfan, M., Ullah, S., Butt, M., Mansoor Javaid, M., Kim, Y., Gaafar, A.-R. Z., Elshikh, M. S., & Hodhod, M. S. (2023). Foliar application of silicon and boron improves boll retention, lint yield and fiber quality traits of transgenic cotton. *Journal of King Saud University - Science*, 35(8). <https://doi.org/10.1016/j.jksus.2023.102858>
- Ali, S., Hafeez, A., Ma, X., Tung, S. A., Chattha, M. S., Ahmad, S., Shah, A. N., & Yang, G. (2023). Potassium-Nitrogen Ratio Improved Cotton Yield by Regulating Antioxidant Metabolism Under a New Cropping Model for the Yangtze River Valley of China. *Journal of Soil Science and Plant Nutrition*, 23(2), 1797–1815. <https://doi.org/10.1007/s42729-023-01138-1>
- Cannea, F. B., & Padiglia, A. (2025). Antioxidant Defense Systems in Plants: Mechanisms, Regulation, and Biotechnological Strategies for Enhanced Oxidative Stress Tolerance. *Life (Basel)*, 15(8). <https://doi.org/10.3390/life15081293>
- Chen, Z., Tao, X., Khan, A., Tan, D. K. Y., & Luo, H. (2018). Biomass Accumulation, Photosynthetic Traits and Root Development of Cotton as Affected by Irrigation and Nitrogen-Fertilization. *Front Plant Sci*, 9, 173. <https://doi.org/10.3389/fpls.2018.00173>
- Chen, Z. J., Sreedasyam, A., Ando, A., Song, Q., De Santiago, L. M., Hulse-Kemp, A. M., Ding, M., Ye, W., Kirkbride, R. C., Jenkins, J., Plott, C., Lovell, J., Lin, Y. M., Vaughn, R., Liu, B., Simpson, S., Scheffler, B. E., Wen, L., Saski, C. A.,...Schmutz, J. (2020). Genomic diversifications of five *Gossypium* allopolyploid species and their impact on cotton improvement. *Nat Genet*, 52(5), 525–533. <https://doi.org/10.1038/s41588-020-0614-5>
- Cheng, Y., Huang, C., Hu, Y., Jin, S., Zhang, X., Si, Z., Zhao, T., Chen, J., Fang, L., Dai, F., Yang, W., Wang, P., Mei, G., Guan, X., & Zhang, T. (2024). *Gossypium purpurascens* genome provides insight into the origin and domestication of upland cotton. *J Adv Res*, 56, 15–29. <https://doi.org/10.1016/j.jare.2023.03.006>
- Coskun, D., Deshmukh, R., Sonah, H., Menzies, J. G., Reynolds, O., Ma, J. F., Kronzucker, H. J., & Belanger, R. R. (2019). The controversies of silicon's role in plant biology. *New Phytol*, 221(1), 67–85. <https://doi.org/10.1111/nph.15343>
- da Silva Liber Lopes, P. M., Campos, C. N. S., Teodoro, P. E., Costa, M. G., de Souza Junior, J. P., & de Mello Prado, R. (2023). The synergistic effects of soil-applied boron and foliar-applied silicon on cotton fiber quality and yield. *BMC Plant Biol*, 23(1), 520. <https://doi.org/10.1186/s12870-023-04542-y>
- de Souza Junior, J. P., de Mello Prado, R., Soares, M. B., da Silva, J. L. F., de Farias Guedes, V. H., dos Santos Sarah, M. M., & Cazetta, J. O. (2020). Effect of Different Foliar Silicon Sources on Cotton Plants. *Journal of Soil Science and Plant Nutrition*, 21(1), 95–103. <https://doi.org/10.1007/s42729-020-00345-4>

- Debona, D., Rodrigues, F. A., & Datnoff, L. E. (2017). Silicon's Role in Abiotic and Biotic Plant Stresses. *Annu Rev Phytopathol*, 55, 85–107. <https://doi.org/10.1146/annurev-phyto-080516-035312>
- Djikanovic, D., Jovanovic, J., Kalauzi, A., Maksimovic, J. D., & Radotic, K. (2025). Effects of Silicon Concentration and Synthesis Duration on Lignin Structure: A Spectroscopic and Microscopic Study. *Biopolymers*, 116(1), e23640. <https://doi.org/10.1002/bip.23640>
- El-Ashmouny, A. A., Hegab, A. S. A., Ali, B. A. A., & Saudy, H. S. (2026). Response of phenological and agronomical attributes and thermal utilization efficiency of cotton cultivars to cumulative heat units under different sowing dates. *BMC Plant Biol*, 26(1), 162. <https://doi.org/10.1186/s12870-025-08076-3>
- El-Beltagi, H. S., El-Warakly, E. A., Al-Daej, M. I., El-Naqma, K. A., Rezk, A. A., Zoghdan, M. G., El-Mogy, M. M., El-Nady, M. F., Ismail, A. M., & Metwaly, M. M. S. (2025). Coupling effects of silicon and calcium foliar application and potassium soil fertilization on growth and yield production of cotton plants under drought stress conditions. *Silicon*, 17(10), 2225–2245. <https://doi.org/10.1007/s12633-025-03333-4>
- Fajardo, J. L. P., de Souza Junior, J. P., Shahid, M. A., Hammond, W., Diepenbrock, L., & Kadyampakeni, D. M. (2025). Silicon and phosphorus impacts on seasonal nutrient dynamics and tree performance of citrus sinensis L. under endemic Huanglongbing conditions. *Front Plant Sci*, 16, 1651108. <https://doi.org/10.3389/fpls.2025.1651108>
- Farooq, M. A., Ali, S., Hameed, A., Ishaque, W., Mahmood, K., & Iqbal, Z. (2013). Alleviation of cadmium toxicity by silicon is related to elevated photosynthesis, antioxidant enzymes; suppressed cadmium uptake and oxidative stress in cotton. *Ecotoxicol Environ Saf*, 96, 242–249. <https://doi.org/10.1016/j.ecoenv.2013.07.006>
- Ferraz, R. L. d. S., Beltrão, N. E. d. M., Melo, A. S. d., Magalhães, I. D., Fernandes, P. D., & Rocha, M. D. S. (2014). Trocas gasosas e eficiência fotoquímica de cultivares de algodoeiro herbáceo sob aplicação de silício foliar. *Semina: Ciências Agrárias*, 35(2). <https://doi.org/10.5433/1679-0359.2014v35n2p735>
- Hodson, M. J., White, P. J., Mead, A., & Broadley, M. R. (2005). Phylogenetic variation in the silicon composition of plants. *Ann Bot*, 96(6), 1027–1046. <https://doi.org/10.1093/aob/mci255>
- Kapeleka, J. A., Ngowi, A. V., Mng'anya, S., Willis, S. E., Salmon, J. P., Tyrell, K. F., Williamson, S., Eddleston, M., & Stuart, A. M. (2025). Assessment of Unintentional Acute Pesticide Poisoning (UAPP) Amongst Cotton Farmers in Tanzania. *Toxics*, 13(4). <https://doi.org/10.3390/toxics13040300>
- Khalequzzaman, Ullah, H., Himanshu, S. K., García - Caparrós, P., Praseartkul, P., Tisarum, R., Chatum, S., & Datta, A. (2024). Exogenous Silicon and Salicylic Acid Applications Enhance Growth, Yield, and Physiological Traits of Cotton Plants under Drought Stress. *Journal of Soil Science and Plant Nutrition*, 24(3), 5947–5960. <https://doi.org/10.1007/s42729-024-01952-1>
- Khan, I., Awan, S. A., Rizwan, M., Ali, S., Hassan, M. J., Brestic, M., Zhang, X., & Huang, L. (2021). Effects of silicon on heavy metal uptake at the soil-plant interphase: A review. *Ecotoxicol Environ Saf*, 222, 112510. <https://doi.org/10.1016/j.ecoenv.2021.112510>
- Khoso, A. R., Jintu, G., Chen, Q., Sheikh, M. J., Suyuhan, W., & Bhutto, S. (2025). Ecological and health impacts of tobacco farming in Pakistan: A mixed-methods approach toward a sustainable pathway for agricultural transition. *Tob Induc Dis*, 23. <https://doi.org/10.18332/tid/201406>
- Kupdhoni, R., Somaddar, U., Khalil, M. I., Ferdoes, J., Das, P., Dey, H. C., Ahmed, M. S., Shams, S.-N.-U., Biswas, P., Sarker, U. K., Uddin, M. R., Mostofa, M. G., & Saha, G. (2025). Silicon application

- improves physiological efficiency and yield of upland cotton by increasing nutrient acquisitions. *Discover Plants*, 2(1). <https://doi.org/10.1007/s44372-025-00400-3>
- Laane, H. M. (2018). The Effects of Foliar Sprays with Different Silicon Compounds. *Plants (Basel)*, 7(2). <https://doi.org/10.3390/plants7020045>
- Li, T., Peng, Y., Yang, J., & You, H. (2024). Robust superhydrophobic cotton fabric based on dual-sized silica particles with self-healing nature. *Int J Biol Macromol*, 267(Pt 1), 131437. <https://doi.org/10.1016/j.ijbiomac.2024.131437>
- Liu, B., Sun, Y., Xue, J., Mao, X., Jia, X., & Li, R. (2019). Stearoyl-ACP Delta(9) Desaturase 6 and 8 (GhA-SAD6 and GhD-SAD8) Are Responsible for Biosynthesis of Palmitoleic Acid Specifically in Developing Endosperm of Upland Cotton Seeds. *Front Plant Sci*, 10, 703. <https://doi.org/10.3389/fpls.2019.00703>
- Lv, T., Bian, M., Chen, F., Chen, C., & Wang, M. (2026). Study of Response of Cotton Productivity in Southern Xinjiang to Planting Patterns and Water-Nitrogen Management. *Plants (Basel)*, 15(4). <https://doi.org/10.3390/plants15040612>
- Malik, M. A., Wani, A. H., Mir, S. H., Rehman, I. U., Tahir, I., Ahmad, P., & Rashid, I. (2021). Elucidating the role of silicon in drought stress tolerance in plants. *Plant Physiol Biochem*, 165, 187–195. <https://doi.org/10.1016/j.plaphy.2021.04.021>
- Mao, X., Zheng, J., Lu, B., Wang, R., Han, W., & Harris, P. (2025). Spatiotemporal drought forecasting in Xinjiang's irrigated agriculture: Model comparison and multi-source data integration. *Journal of Hydrology*, 660. <https://doi.org/10.1016/j.jhydrol.2025.133483>
- Niu, J., Liu, C., Huang, M., Liu, K., & Yan, D. (2020). Effects of Foliar Fertilization: a Review of Current Status and Future Perspectives. *Journal of Soil Science and Plant Nutrition*, 21(1), 104–118. <https://doi.org/10.1007/s42729-020-00346-3>
- Rabeh, H. A., El-Motaium, R. A., & Badawy, S. H. (2023). Nano-silicon and boron foliar applications for promoting growth, yield, and fiber quality of Egyptian cotton (*Gossypium barbadense* L.). *Journal of Plant Nutrition*, 46(15), 3617–3632. <https://doi.org/10.1080/01904167.2023.2209114>
- Ren, Y., Sun, Z., Hu, X., Liu, Q., Xu, Q., Qin, D., Wang, X., Liu, S., Ma, C., & Wei, X. (2023). Effects of Different Nitrogen Allocation Ratios and Period on Cotton Yield and Nitrogen Utilization. *Water*, 15(16). <https://doi.org/10.3390/w15163011>
- Saha, G., Mostofa, M. G., Rahman, M. M., & Tran, L. P. (2021). Silicon-mediated heat tolerance in higher plants: A mechanistic outlook. *Plant Physiol Biochem*, 166, 341–347. <https://doi.org/10.1016/j.plaphy.2021.05.051>
- Santos, A. F. B. d., Teixeira, G. C. M., Campos, C. N. S., Baio, F. H. R., Prado, R. d. M., Teodoro, L. P. R., Vilela, R. G., Paiva Neto, V. B. d., & Teodoro, P. E. (2020). Silicon increases chlorophyll and photosynthesis and improves height and NDVI of cotton (*Gossypium hirsutum* L. r. latifolium Hutch). *Research, Society and Development*, 9(7). <https://doi.org/10.33448/rsd-v9i7.3826>
- Shah, T., Khan, H., Ali, A., Khan, Z., Alsahli, A. A., Dewil, R., & Ahmad, P. (2024). Silicon and arbuscular mycorrhizal fungi alleviate chromium toxicity in Brassica rapa by regulating Cr uptake, antioxidant defense expression, the glyoxalase system, and secondary metabolites. *Plant Physiol Biochem*, 206, 108286. <https://doi.org/10.1016/j.plaphy.2023.108286>
- Song, F., Yang, Q., Huang, J., Guo, Z., Li, Y., & Deng, W. (2026). Plant drought stress: physiological, biochemical and molecular mechanisms. *Plant Stress*, 19. <https://doi.org/10.1016/j.stress.2025.101153>
- Sultan, H., Chen, J., Faizan, M., Xue, T., Wan, H., & Zeng, C. (2026). Carbon to nano-carbon:

comparative efficacy of conventional biochar and SiO₂-nanoparticles inoculated biochar in enhancing physiological, anatomical, and molecular salt tolerance in rice. *Plant Physiol Biochem*, 232, 111081. <https://doi.org/10.1016/j.plaphy.2026.111081>

Wang, M., Wang, R., Mur, L. A. J., Ruan, J., Shen, Q., & Guo, S. (2021). Functions of silicon in plant drought stress responses. *Hortic Res*, 8(1), 254. <https://doi.org/10.1038/s41438-021-00681-1>

Wang, X., Li, J., Zhang, J., Yang, L., Cui, W., Han, X., Qin, D., Han, G., Zhou, Q., Wang, Z., Zhao, J., & Lan, Y. (2024). Estimation of Cotton SPAD Based on Multi-Source Feature Fusion and Voting Regression Ensemble Learning in Intercropping Pattern of Cotton and Soybean. *Agronomy*, 14(10). <https://doi.org/10.3390/agronomy14102245>

Yu, L., Luo, X., Croft, H., Rogers, C. A., & Chen, J. M. (2024). Seasonal variation in the relationship between leaf chlorophyll content and photosynthetic capacity. *Plant Cell Environ*, 47(10), 3953–3965. <https://doi.org/10.1111/pce.14997>