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The efficiency of silicious nano nutrition on cotton productivity in arid regions

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Since silicon (Si) was found to be effective in crop production recently, more information is needed about its characteristics, including how it functions as a nano fertilizer for crop performance. Therefore, this study aimed to evaluate the impact of the Si-containing nano fertilizer on cotton growth parameters and productivity in the arid region. The research conducted in open field conditions over the two consecutive growing seasons (2021 and 2022) revealed that the application of the Si-containing product significantly increased the biomass (10.6%), economic (19.4%), seed (14.3%), and lint yields (18.2%) of cotton as compared to the control group values. Likewise, the cotton biomass, economic, seed, and lint yields were increased by 11.8, 9.7, 9.5, and 9.1%, respectively, compared to the control variables after the Uzbiogumin application. Agronomic nitrogen-use efficiency (aNUE), physiological nitrogen-use efficiency (pNUE), internal nitrogen-use efficiency (iNUE), and apparent nitrogen recovery efficiency (aNRE) parameters were increased by 2.4-fold, 2.1-fold, 34.6 and 57.3%, respectively, with the application of Si nanonutrition. Although the cotton treated with nano Si produced a greater yield, while Uzbiogumin application resulted in more cotton biomass. Based on the results it can be concluded that the applied nano Si product can be widely used to increase crop productivity, especially in degraded lands under arid environments.

KEYWORDS

arid region, cotton, foliar treatment, nano nutrition, nutrient use efficiency, Si fertilizer, yield

Introduction

Intensive crop production along with the challenges of man-induced climate change have already created many constraints for agriculture in arid regions. The extensive use of chemical fertilizers and pesticides considerably degraded ecosystems and the environment, leading to a decline in soil structure and eventually posing a risk to public health (Khaitov et al., 2019). Long periods of intensive land management operations such as salt leaching, cultivations and weathering caused desilication and nutrient removal from the soil, deteriorating soil health and related agroecosystem functions (Namozov et al., 2022). Estimates indicate that by 2050, the trend of agricultural output will not be enough to fulfill the rising demand brought on by population growth if innovative technologies are not invented and implemented (Kretschmer and Kahl, 2021).

Fertilizer advancements like the use of Si fertilizer can have a significant impact on crop characteristics and help to increase overall productivity. Because they are noncorrosive and pollution-free, Si fertilizers (both organic and inorganic) are high-quality fertilizers that are regarded as sustainable and eco-friendly for agriculture (Yilmas and Korkmas, 2023). Several studies have reported that future sustainable agricultural production will more likely be associated with the potential impact of nanotechnology (Kah et al., 2018; El-Desouky et al., 2021). Precision nutrient management strategies using nano fertilizers are becoming more common in agriculture (Barzana et al., 2022; Arifur Rahman et al., 2024). In recent years, several nano materials have been tested for their efficacy and reactivity to stimulate the vegetative and generative development of different crops (Hossain et al., 2017; Arifur Rahman et al., 2024).

Cotton is a widely used and high-value economically important crop that adapted well to arid and harsh environments. Uzbekistan is one of the leading cotton producers in the world, despite its production has been declining substantially in the last few years (Allanov et al., 2019). So far, there have been extensive studies regarding the effect of chemical and biological fertilizers on crop productivity. However, less work has been performed on cotton performance in response to the effect of nano nutrition.

A stimulative effect due to foliar silicon application is shown in plants' responses to stressful environments like salt, excessive or insufficient water, extreme heat or cold, and intense disease and insect pressure, among other things (Coşkun et al., 2016). To decrease oxidative damage brought on by water and salt loss by transpiration, silicon offers suberization, lignification, and silicification in the cell wall (Shen et al., 2010). The recent research on salt stress revealed that Si application could enhance water content in plants by enhancing root water absorption (Wang et al., 2015; Zhu et al., 2015), improve nutrient uptake (Aqeel et al., 2022), increase nutritive value and productivity of crops (Rahman et al., 2023).

This silicon-based foliar feeding is a far more affordable and practical method than soil fertilizer, and it enhances the water and nutrient use efficiency of crops in arid conditions as well as enhances the protein and oil contents of produced products (Deshmukh et al., 2017). So, the wide-scale use of Si fertilization may also be feasible, and the food supply will benefit from the smart fertilizer in the future. Therefore, more studies can shed light on Si fertilizer management practices and help to promote Si as an innovative approach for precision agriculture, sustainability and enhancement. This study hypothesized that if this novel nanoparticle technology can stimulate crop biological processes in challenging conditions, it might significantly enhance cotton productivity.

The effectiveness and sustainability of the recently discovered material on crop productivity should also be a priority, utilizing the positive multifunctional effects of new products in stressful situations. Despite this, relatively little research was done using nanotechnology to growth, nutrient uptake and yield of cotton in arid zones. Thus, efforts should be made to ascertain the impact of Si fertilizer on cotton performance under harsh environments.

Materials and methods

Experiment area and environmental conditions

This open-field experiment was conducted at the experimental station of the Cotton Breeding, Seed Production, and Agrotechnologies Research Institute in Kibray district, Tashkent region, Uzbekistan (Altitude: 271 m, Latitude: 40°25′ North, Longitude: 68°40′ East) over the two consecutive growing seasons (2021 and 2022). This area has four distinct seasons and a mostly continental dry climate. Underground water is located at 18–20 m depth. The growing season for crops is hot and largely dry, with heat stress often preceding droughts. The air temperature was recorded as low as 0°C in January and as high as 38°C in July. No frost days range between 240 and 270 per year. The range of the average yearly rainfall is 210–245 mm. Most crops do not generally benefit from the rainfall, since the large portion occurs out of the growing season (Figure 1).

Experiment materials

Silicon-based fertilizer "*Sila kremniy*"® constitutes complex nano mineral substances including Si 17–22%, Fe 1–4%, Cu 0.05–0.1%, Zn 0.05–0.1%, and S, Ca, Mg, and etc. The hydrogen index (HI) at 0.05% solution is 6.5–7.5, with density at +20ºC not less than 1.3 g/cm^3. This nano fertilizer strengthens the immune system, biochemical processes, metabolism, growth, and crop yield.

Uzbiogumin is a dark brown liquid consisting of humic acids. It also contains biologically active substances such as potassium and sodium humates, fulvic acids, trace elements, amino acids, enzymes, and natural compounds.

Sultan cotton variety has been created by selection, breeding, and hybridization interspecies techniques at the Scientific Research Institute of Agrotechnologies by Sh. Namazov, P.Ibragimov and others. In 2009, this cotton variety was registered in the State Committee. The vegetation cycle period is 115–120 days. Productivity 40.0–48.3 dT/ha. The weight of cotton boll is 6.0–6.5 g. Fiber length 33.0–34.0 mm, fiber yield 36.0–37.0%, fiber softness 5,800–6,000, hardness 4.5–4.8 g, breaking length 26.1–31.7 gk/tex, fiber type-V, micronairy-4.4-4.5, early ripening, and high-yielding variety.

Treatment methods of the nanofertilizers

The Si nanofertilizer was obtained from the Viktor® company (Tashkent, Uzbekistan) and Uzbiogumin from the Plant Chemistry

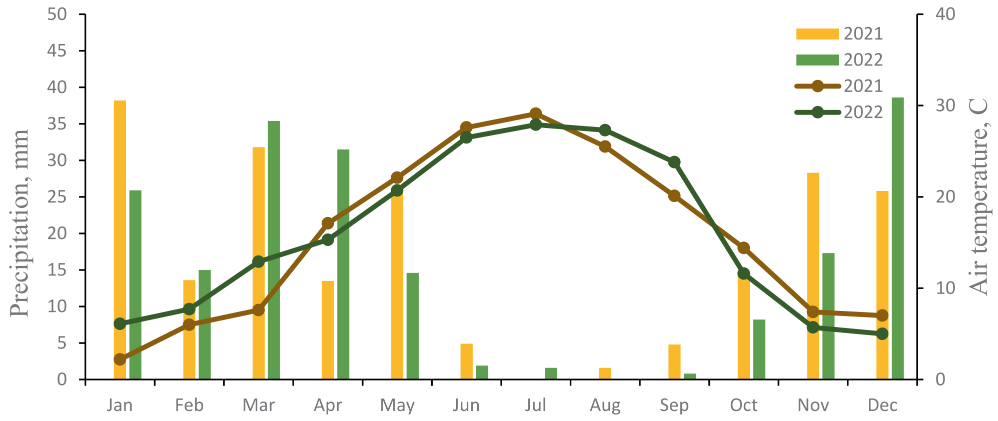

FIGURE 1
Weather conditions during the cotton growing season years 2021–2022.

Research Institute (Tashkent, Uzbekistan). The nano Si treatments were applied to cotton seeds before sowing and twice at the vegetative period, in early June and early July, with respective doses indicated in Table 1. For the seed treatment, 100 mL Si nano fertilizer was diluted in 0.5 L water. After shaking for 15 min, this substrate was added to 20 L water for the treatment of 1 ton cotton seeds. Similarly, 1.4 L Uzbiogumin was diluted in 20 L of water and sprayed to 1 ton of cotton seeds 2 h before planting.

During the vegetation period, the respective doses (Table 1) of these nano fertilizers were added to 200 L of water and sprayed with high pressure to vegetative parts of the plant.

Agrotechnique activities and experiment design

Cotton was planted in this experimental field for two consecutive cotton growing seasons (2021 and 2022). The experimental field was cleaned from plant residues before autumn plowing. The yearly doses of chemical fertilizers, i.e., nitrogen 200 kg ha^{-1}, phosphorous 140 kg ha^{-1}, and potassium 100 kg ha^{-1} were divided into three portions. The first fertilizer application was conducted in early spring, phosphorous and potassium fertilizers were broadcasted with disking. During the growth season, chemical fertilizers were given as a band placement. Cotton seeds were planted in the middle of April in both experimental years, followed by herbicide treatments with Stomp® at 2 L ha^{-1}. When cotton seedlings were grown up, hand weeding was conducted. Inter-row cultivation activities with machinery were done five times. The experimental field was irrigated five times at a norm of 800 m^3 as a furrow technique. Crop cultivation technologies, such as irrigation, pest management, and weed control, were carried out in compliance with local agronomic standards while keeping all trials identical.

The study utilized a randomized complete block design with split-plots and three replications.

The experiment was conducted in three main plot treatments consisting Si nanotreatment, Uzbiogumin application and control. The three replications were arranged in three blocks.

There was a total of 24 plots (each measuring 4.8 m × 10 m = 48 m^2) and 1,152 m^2 in the experiment area. Si nano fertilizer and Uzbiogumin were applied three times to the tested cotton genotype during the vegetation period as per the manufacturer's instructions (Table 1).

TABLE 1 Application period and doses of the nanofertilizers.

Treatments	Seed preparation stage	Budding stage	Flowering stage
Control	-	-	-
Si	100 mL/ton	150 mL/ha	210 mL/ha
Uzbiogumin	1.4 L/ton	0.4 L/ha	0.6 L/ha

Soil and plant nutrient analysis

Before chemical analysis, cotton shoots that were randomly picked just before harvesting and cleaned by spraying them with distilled water, oven-dried for 24 h at 65 degrees Celsius, crushed through a 0.5-mm screen, and then sealed in plastic bags.

Total P in acid digestate was determined spectrophotometrically using the ascorbic acid technique, whereas total N was evaluated using the micro-Kjeldahl method (Chapman and Pratt, 1961). The samples in a 50 mL digestion tube with a weight of 0.150 g each were treated 3.5 mL of concentrated sulfuric acid (H_2SO_4) using an acid resistant 5-mL repipet device and then heated on a hot plate to 180°C to decompose for a 1 h. The tubes were removed from the heating block to allow about 20 min for cooling before further procedures. Using flame photometry, the total Ca, Mg, and K in the diluted acid digestate were measured (Murphy and Riley, 1962).

Nitrogen-use efficiency

1 *Agronomic nitrogen-use efficiency* (aNUE) exhibits the yield increase due to the per unit of N supplied (Y_f) as compared to the control (Y_0) treatment (Fageria and Baligar, 2003):

$$\text{aNUE}\left(\text{kg}\,\text{kg}^{-1}\right) = \left(Y_f - Y_0\right) / \text{N fertilization}$$

2. *Physiological nitrogen-use efficiency* (pNUE) was determined based on the increase in cotton yield per unit of increased N uptake (Isfan, 1990):

$$\text{pNPE}\left(\text{kgkg}^{-1}\right)=\left(\text{Y}_{\text{f}}-\text{Y}_0\right)/\left(\text{TNU}_{\text{f}}-\text{TNU}_0\right)$$

   Where, the TNU_f and TNU_0 are the N uptake in N fertilized-and the control plots, respectively.

3. *Internal nitrogen-use efficiency* (iNUE) was determined considering on cotton yield increase per unit tissue N concentration (Witt et al., 1999):

$$\text{iNUE}\left(\text{gg}^{-1}\right)=\text{Cotton yield / Tissue N concentration}$$

4. *Apparent nitrogen recovery efficiency* (aNRE) was found based on the increased total N uptake in response to N fertilization (Dilz, 1988):

$$\text{aNRE}\left(\%\right)=\left[\left(\text{TNU}_{\text{f}}-\text{TNU}_0\right)/\text{ N fertilization}\right]^{*}100$$

   Where, the TNU_f and TNU_0 are the N uptake in N fertilized-and the control plots, respectively.

Statistical analysis

To investigate the impact of nano nutrient applications on cotton growth, nutrient uptake and productivity, a statistical study was carried out using the ANOVA (CropStat, 2015) statistical software program. Least significant difference (LSD) techniques were used to isolate significant mean values. Statistical comparisons ($p = 0.05$) obtained from three replications were used to determine the impact of the two used nanofertilizers on cotton vegetative and generative indicators.

Results and discussion

Plant growth and yield characteristics

As seen in Table 2, the effect of the tested treatments was substantial from the early vegetation stage, as the seed germination increased by 29.7 and 18.5% due to the Si and Uzbiogumin applications, respectively, compared to the control values. No statistical differences were found in the plant stand density indicators among the applied treatments, strongly ensuring the accuracy of the field observation data. A significant increase in cotton growth characteristics was observed with Uzbiogumin treatment, when the vegetative growth metrics, i.e., plant height, fruit branches and cotton boll, were 4.4, 15.7, and 16.1% higher, respectively, compared with those of the control plants. However, cotton generative characteristics were more pronounced with Si fertilization during both experimental years, i.e., numbers of fruit branches and cotton boll values increased by 26.4 and 30.1%, respectively, than those of the control conditions.

When Si fertilizer was sprayed on cotton seeds and vegetative parts, the morphologic parameters showed a positive reaction in response to the Si treatment. Furthermore, insect damage was greatly decreased due to the application of Si along with other microelements, which ensured healthy plant growth. This outcome is in line with some previous studies; however, its preventive qualities differ in degree between species and are also dependent on environmental variables (Li et al., 2015; Wang et al., 2015; Coşkun et al., 2016). Previous studies also confirmed that plants' Si absorption protects against fungal diseases, thereby reducing the risk in terms of quality and quantity (Artyszak, 2018).

The soil–plant system is impacted by silicon fertilization in two different ways. First, it enhances plant nutrition and boosts plant resilience to pests, diseases, and unfavorable stress factors, including salt, dehydration, heavy metals, and hydrocarbon toxicity. Second, soil treatment with biogeochemically active Si compounds enhances soil fertility by maintaining nutrients in plant-available forms and improving hydrologic, physical, and chemical soil qualities (Tripathi et al., 2016; Snehal and Lohani, 2018) (Table 3).

As shown in Table 4, the highest total yield of 7.3 Mg/ha was achieved at the Si treatment, followed by the Uzbiogumin application with 7.2 Mg/ha total yield, and the lowest total yield was 6.6 Mg/ha at the control variable. The Si treatment significantly increased the biomass (10.6%), economic (19.4%), seed (14.3%), and lint yields (18.2%) of cotton as compared to the control values. Likewise, the cotton biomass, economic, seed and lint yields were increased by 11.8, 9.7, 9.5, and 9.1%, respectively, compared to the respective control values after the Uzbiogumin application. A consistent and significant effect on the total yield values was obtained compared to the control value when plants were treated with the Si fertilizer and Uzbiogumin. Although the effect of the Si fertilizer was higher than that of Uzbiogumin, it did not reach a significant level in terms of total yield. However, the Si treatment had a greater impact on the economic, seed, and lint yields than the Uzbiogumin application.

These findings may be explained by the increased reliance on cotton production, which is positively associated with the

TABLE 2 Effect of nanofertilizers on cotton growth characteristics.

Treatments	Germination, (%)	Morphological characteristics at 01.09.			
		Stand density (1,000 plant ha^{-1})	Plant height (cm)	Fruit branches (number plant^{-1})	Cotton boll (number plant^{-1})
Control	64.7c	66.2a	92.6ab	12.1c	9.3c
Si	83.2a	65.2a	95.1a	15.3a	12.1a
Uzbiogumin	76.7b	66.8a	96.7a	14.0b	10.8b

Means in each column exhibited by lowercase letters (a–c) differ significantly at $p < 0.05$.

TABLE 3 Effects of Si fertilization on total, biomass, economic, seed, and lint yields of irrigated cotton in saline soil under continental climate (Averaged across 2021 and 2022 growing seasons).

Treatments	Total	Biomass	Economic	Seed	Lint yield
	yield (Mg/ha)				
Control	6.6b	3.4c	3.2c	2.1b	1.1c
Si	7.3a	3.6b	3.7a	2.4a	1.3a
Uzbiogumin	7.2ab	3.8a	3.4b	2.3ab	1.2b

Means exhibited by lowercase letters (a–c) in each column differ significantly at $p < 0.05$.

nano-nutrition strategy. According to several studies, nano Si treatment typically boosts yield by 10–25 per cent depending on crop species, application period and doses (Ahmad et al., 2016; Iqbal, 2019). This applied nanotechnology has become more prevalent in agriculture by enhancing agricultural economics, reducing losses, and boosting farm incomes through precision nutrient management practices (Barzana et al., 2022).

The wide-scale application of silicious nano fertilizers for cotton production has the potential to maximize yield, making it the most effective treatment under challenging climatic conditions in arid regions.

Soil chemical properties

It was determined that the soil of the experimental field was not fertile, as seen in humus, nitrogen and phosphorus in total and available forms are much lower than the average values (Table 4). The amount of humus was 0.720% in the 0–15 cm soil layer of the soil, the total forms of nitrogen 0.078%, phosphorus 0.160%, in the available forms $N0_3$ –2.9, P_20_5 —16.2 and K_2O —276 mg/kg. A decreasing trend of these characteristics was observed in the deeper soil horizons. In the 15–30 cm soil profile, the amount of humus was 0.68%, total nitrogen 0.76%, phosphorus 0.161%, available NO_3 –2.3, P_2O_5 –14.0, and K_2O –266 mg/kg. Intensive crop production deteriorated the biological processes of this land substantially, harming nutrient balance in the soil.

Nutrient uptake and efficiency

The tested nano fertilizers increased cotton shoot N, P, Ca, and Mg concentrations. At the same time, the impact of the Si treatment was significantly higher than that of the Uzbiogumin treatment (Table 5). The Si fertilizer considerably increased the total N concentration by 2.14-fold when compared to the control value. Similarly, P, Ca, and Mg concentrations of cotton plants under the Si treatment were greater than those of the corresponding controls by 1.91-fold, 36.5 and 28.6%, respectively.

Uptake of total N, P, and Ca were significantly higher by 1.4-fold, 1.91-fold and 36.5% compared to the respective control values when the Uzbiogumin treatment was used. However, Ca uptake did not vary significantly with the nano nutrition application. In contrast, Mg uptake also increased significantly after the nano nutrition.

Recent studies have shown that silicon-based foliar feeding further increases the efficiency of macro and micro fertilizers, i.e., N, P, K, Ca, Fe, Mn, Cu, and Zn (Neu et al., 2017). As highlighted by Miyatake et al. (2019) the assimilation processes of microelements are closely interlinked in plants because of protein compositions.

TABLE 4 Soil chemical properties.

Soil profiles	Humus content, %	Total forms, %		Available forms, mg kg^{-1}		
		N	P	NO_3	P_2O_5	K_2O
0–15	0.72	0.85	0.160	2.9	16.9	289
15–30	0.68	0.76	0.156	2.3	14.6	266
30–60	0.51	0.72	0.155	1.9	11.0	246
60–90	0.46	0.68	0.144	1.5	10.3	235

According to Zhu and Gong (2014), silicon treatments enhanced photosynthetic rates, provided nutritional balance, decreased water loss from leaves, and boosted root absorption of water. It was found that silicon treatments enhance the activity of antioxidant and nonantioxidant enzymes, shielding plants from the oxidizing effects of salt (Bakhat et al., 2018). Additionally, silicon treatments contributed to the control of osmatic processes, which in turn enhanced the activity of photosynthetic enzymes.

Crops need the optimum supply of macro and micronutrients to withstand biotic and abiotic stresses, even effectively alleviating salinity and drought-induced hazardous effects (Shahid et al., 2015). Adequate nutrient management in plants may be better able to withstand drought stress by maintaining or even increasing their water use productivity (Hamayun et al., 2010; Yin et al., 2019). The increase of nutrient uptake indices due to nanonutrition delivers the best crop production (Kaushik and Saini, 2019) which may result in a new practical approach to sustainable agriculture with a higher NUE while conserving water and nutrient resources.

As the results in Table 6 showed, applying the nano fertilizers led to a significant increase in nutrient uptake by cotton. Total N, P, and K uptake by cotton was significantly higher with the nano fertilization. N uptake varied significantly between the used treatments, while the mean value ranged from 87.4 to 107.0 kg ha^{-1}. Likewise, the maximum P uptake was 27.8 kg ha^{-1}, observed in the Si treatment, and the minimum value was 19.4 kg ha^{-1} for the control group.

K, Ca and Mg uptake parameters were also significant within the applied treatments. The N, P and K uptake was more pronounced with the Si treatment than the Uzbiogumin application.

As expected, foliar Si nano nutrition promoted plant growth and consequently increased the demand for other nutrients. Significantly higher N, P, and K uptake by cotton with Si application was probably related to improved nutrient balancing and greater nutrient adsorption.

Recent studies also showed that treatments with silicon decreased the buildup of salt in roots and shoots under stress conditions like

TABLE 5 Effects of nano fertilization on shoot total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentration of cotton under arid climate (Averaged across 2021 and 2022 growing seasons).

Treatments	N	P	K	Ca	Mg
			(%)		
Control	2.17c	0.23c	0.36a	0.52c	0.14c
Si	4.64a	0.44a	0.38a	0.71a	0.18a
Uzbiogumin	3.04b	0.39b	0.37a	0.68b	0.17ab

Means exhibited by lowercase letters (a–c) in each column differ significantly at $p < 0.05$.

TABLE 6 Effects of nano fertilization on total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) uptake by irrigated cotton under continental climate (Averaged across 2021 and 2022 growing seasons).

Treatments	N	P	K	Ca	Mg
		(kg/ha)			
Control	87.4c	19.4c	64.4c	14.9c	3.8c
Si	96.2b	27.8a	95.9a	18.8a	4.8a
Uzbiogumin	107.0a	23.9b	82.7b	16.3b	4.5b

Means exhibited by lowercase letters (a–c) in each column differ significantly at $p < 0.05$.

TABLE 7 Effects of nitrogen fertilization with Azovit on nitrogen-use efficiency of irrigated cotton under continental climate (Averaged across 2021 and 2022 growing seasons).

Treatments	aNUE ($kg\ kg^{-1}$)	pNUE	iNUE ($g\ g^{-1}$)	aNRE (%)
	($kg\ kg^{-1}$)			
Control	1.9c	26.6c	13.6c	11.7c
Si	4.5a	56.8a	18.3b	18.4a
Uzbiogumin	3.1b	31.3b	16.0a	14.8b

Means exhibited by lowercase letters (a–c) in each column differ significantly at $p < 0.05$.
aNUE, Agronomic nitrogen-use efficiency; pNUE, Physiological nitrogen-use efficiency; iNUE, Internal nitrogen-use efficiency; and aNRE, Apparent nitrogen recovery efficiency.

salinity and drought (Zhu et al., 2015). According to Li et al. (2015), Si increased crop root hydraulic conductivity and growth, which increased root water intake and further enhanced leaf water content. In this regard, multidisciplinary research should be focused on exploring more in detail the effect of the nano form of Si for alleviating the effects of salt and drought stress (Cooke and Leishman, 2016).

It is more likely that the crop did not experience any nutrient stress at any development stages when the nano fertilizers were applied as per guidance. Increased partitioning and diversion of assimilates from vegetative development to reproductive growth of cotton was positively facilitated by the Si application.

As can be inferred from Table 7, the effects of the nano fertilizers on the nitrogen-use efficiency indices were found to be significant at $p < 0.05$ level in all measured parameters. Agronomic nitrogen-use efficiency (aNUE), physiological nitrogen-use efficiency (pNUE), internal nitrogen-use efficiency (iNUE), and apparent nitrogen recovery efficiency (aNRE) parameters were increased by 2.4-fold, 2.1-fold, 34.6 and 57.3%, respectively, with the application of the Si treatment compared to the control group. The effect of Uzbiogumin was also significantly higher than the control group, increasing aNUE, pNUE, iNUE, and aNRE by 1.63-fold, 17.7, 17.7, and 26.5%, respectively.

The ratio of the plant's intake of N compared to the total quantity of N fertilizer is considered as N utilization efficiency or NUE. An increase in N fertilizer efficiency is vitally important for sustainable agriculture, particularly NUE optimization aimed at increasing cotton production. In this experiment, the NUE indices following the Si treatment were significantly greater than that of the Uzbiogumin application, which resulted in a significantly higher yield per unit of N fertilizer applied.

In recent experiments, Silicon treatments boosted photosynthetic rates, decreased water loss from leaves, increased water absorption by roots, and provided nutritional balance (Zhu and Gong, 2014). Furthermore, silicon treatment stimulates the activity of non-antioxidant and antioxidant enzymes, reducing the ability of salt to oxidize plants and contributing to osmatic control, which in turn improves the activity of photosynthetic enzymes (Siddiqui et al., 2014). Additionally, researchers found that silicon treatments decreased salt buildup in roots and shoots, increasing the salt tolerance of crops (Amin et al., 2016). According to recent reports, Si helps plants become drought-tolerant by controlling their transpiration, stomatal conductance, and relative water content in their leaves (Li et al., 2015).

As a crucial indicator of NUE, the iNUE shows how applied N is efficiently absorbed and used by the plant to convert N from the soil into economic yield. Increasing the iNUE is essential to raise crops' quality and productivity without a detrimental impact on the environment (Ali et al., 2022). Using this nano nutrition with appropriate NUE maintains higher crop productivity and increases the efficiency of supplied chemical fertilizers. A variety of physiologically active substances, including macro-and microelements, vitamins, and growth regulators, are included in the majority of biostimulants (Zewail et al., 2020). Silicon-based fertilizer "Sila kremniy"® also includes N, Ca, Bo, Mg, Fe, Zn, Mn, and Mo and many microelements essential for normal plant growth even in a stressful environment. This is likely related to the extensive crop cultivation over the years that has caused silica and other nutrients to be lost from agricultural soils, limiting the efficiency of irrigation and nutrient resources. These micro and nano nutrient elements are essential to the global food supply chain, and Si-based fertilizers are expected to be extensively utilized in agriculture in the future. Moreover, the environment and ecosystems are being harmed by the increasing use of chemical pesticides and fertilizers, which increases the risks to human health and biodiversity (El-Desouky et al., 2022). Shi et al. (2016) also declared that crop nano-nutrition practices contribute to the development of incentives for climate-smart agriculture while maintaining the natural resources and ecosystem functions.

However, there are still a lot of questions concerning the potentially effective means of Si fertilizers and their role in reducing chemical fertilizer application. Thus, multi-scale science-based validations is needed to accelerate the process of considering Si fertilizers as a sustainable agricultural management strategy in challenging environmental settings.

Conclusion

This study proved that the Si nano nutrition significantly improved cotton performance, i.e., cotton growth, NUE and productivity, and fortified against environmental stresses. Applying the Si-containing product significantly increased the total cotton biomass by 10.6%, economic yield by 19.4%, seed yield by 14.3% and lint by 18.2% compared to the control group values. Likewise, against the control variables, the cotton biomass, economic, seed and lint yields were increased by 11.8, 9.7, 9.5, and 9.1%, respectively, after the Uzbiogumin application. The cotton treated with Uzbiogumin accumulated more biomass, but the nano Si applied cotton generated a higher yield. Thus, the Si treatment positively facilitated increased partitioning and diversion of assimilates from vegetative to reproductive growth.

With the development of nanotechnology, newly discovered nanomaterials often bring perspectives and sustainability in crop production that might facilitate as a driver of climate-smart agricultural practices under stressful environments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

BoK: Data curation, Writing – original draft, Writing – review & editing. SA: Conceptualization, Writing – original draft, Writing – review & editing. KA: Investigation, Writing – original draft, Writing – review & editing. BaK: Methodology, Writing – original draft, Writing – review & editing. MiA: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. SI: Formal analysis, Validation, Writing – original draft, Writing – review & editing. UN: Resources, Writing – original draft, Writing – review & editing, Methodology, Visualization. KS: Methodology, Writing – original draft, Writing – review & editing, Resources, Visualization. RY: Data curation, Writing – original draft, Writing – review & editing, Formal analysis. NR: Formal analysis, Writing – original draft, Writing – review & editing. GM: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. MuA: Data curation, Methodology, Writing – original draft, Writing – review & editing. GB: Investigation, Software, Writing – original draft, Writing – review & editing. YR: Data curation, Methodology, Writing – original draft, Writing – review & editing. MI: Investigation, Software, Writing – original draft, Writing – review & editing. OO: Resources, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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