frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 November 2025
DOI 10.3389/fsufs.2025.1695604

OPEN ACCESS

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RECEIVED 30 August 2025
ACCEPTED 24 October 2025
PUBLISHED 12 November 2025

CITATION
Israilov I, Sindarov O, Salomov S, Khayitov K, Bobokulov S, Begmatov I, Isabaev K, Uspankulov B, Khasanova O, Tungushova D, Turakulov D, Karimova K, Karimov M, Kenjayev R and Khaitov B (2025) Agronomic efficiency of nano-integrated nutrient management on cotton yield traits under arid farming conditions.
Front. Sustain. Food Syst. 9:1695604.
doi: 10.3389/fsufs.2025.1695604

Agronomic efficiency of nano-integrated nutrient management on cotton yield traits under arid farming conditions

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Cotton (*Gossypium* spp.) is a globally cultivated climate resilience fiber crop known for its potential to produce substantial biomass and yield in stress environments. However, its production requires a huge amount of chemicals, bringing harm to the environment and ecosystem services. Field studies during the 2023–2024 growing seasons were focused on agronomic parameters of cotton in response to nano (Si and Uzbi) and three chemical fertilizer regimes (N_{150} P_{105} K_{75}; $N_{200}P_{140}$ K_{100}; $N_{250}P_{175}K_{125}$) under arid condition of Uzbekistan. The experiment was arranged in a split-plot design with three replications. The application of nano Si improved nutrients uptake and yield parameters of cotton under open-field arid environment due to a positive synergism between nano and chemical fertilization. The effect of Si nano compound was more pronounced at the lower fertilizer regime ($N_{150}P_{105}K_{75}$), exhibiting the increase of cotton yield by 31.3% and 1000 seed weight by 5.32% than those in the control. On the other hand, the Uzbi treatment exhibited high efficacy at the intermediate fertilizer level ($N_{200}P_{140}K_{100}$), enhancing total cotton biomass by 12.9% and total yield by 26.3% relative to the control. The Si nano was found to be relatively efficient in terms of NUE, crop yield and may help reduce the reliance on excessive chemicals in current climate changing scenario. This study explored the cost-effective pathways toward more sustainable cotton production through the synergistic combination of nano and chemical fertilizers in irrigated arid agricultural regions.

KEYWORDS

cotton, nano fertilizers, chemical fertilizer, nutrient uptake, nutrient use efficiency, cotton yield

1 Introduction

Agricultural modernization is crucial to global food security, ensuring sustainable production of essential crops, livestock, and raw materials that are needed for human consumption, nutrition, health, and economic stability. Most used conventional farming practices often lead to excessive use of chemical fertilizers and pesticides, soil degradation, and environmental pollution (Allanov et al., 2019). Moreover, increased soil salinity resulted in toxic buildup in soil and water, and disrupted the natural balance of biological systems, posing potential risks on ecosystem functionality (Nurbekov et al., 2023).

The introduction of climate resilient practices that contribute to food production are of great importance to mitigate and adapt to climate change, as well as to enhance food security. Advanced science-driven innovations play an important role in agriculture by upgrading fertilizer formulations to improve plant nutrient uptake, reduce nutrient losses, enhance plant stress tolerance and increase crop productivity (Zakzok et al., 2022). These innovative climate-smart practices can be used for sustainable agricultural production, considering the documented role of modern agrotechnologies in boosting global food production.

Cotton (*Gossypium* spp.) is a globally cultivated fiber and oilseed crop known for its adaptability to diverse and challenging environmental conditions. It thrives well in irrigated arid climates and demonstrates notable resilience to abiotic stresses such as drought, salinity and heat. Cotton requires large amounts of chemical fertilizers and nutrient deficiency is considered as the main constraint for cotton production in irrigated agriculture of Uzbekistan (Nurbekov et al., 2024).

Despite the implementation of engineered innovative strategies, only about half of the applied N is utilized by crops under favorite conditions (Verma et al., 2023). This problem could be solved by the adoption of breakthrough innovations and highly effective sustainable solutions such as fertilizer advancement (Khaitov et al., 2020). Nano compounds serve as an effective means to enhance crop productivity, offering a sustainable, safe, and renewable supply of essential plant nutrients in optimal and balanced concentrations. Their use can reduce chemical fertilizer (NPK) application rates by up to 50%, without negatively impacting plant growth or yield (Sajjan et al., 2025). Implemented climate-resilient agricultural practices should sustain crop productivity, enhance resource efficiency, and promote sustainable soil management, contributing to long-term food security. Moreover, adopting precision agriculture principles can enhance soil health and mitigate greenhouse gas emissions, thereby supporting sustainable ecological functions and ecosystem services (Reda et al., 2025). Thus, cross-disciplinary studies are necessary, combining diverse skills and knowledge to develop science-based cutting-edge solutions (Hussein and Abou-Baker, 2018). Since land and water resources are limited, it is necessary to maximize the productive capacity of degraded soil, manage organic matter effectively, and enhance water use efficiency, thereby developing climate resilience in farming. Special attention will also be paid to techniques that enhance the productive capacity of degraded soil, manage soil organic matter, and improve water use, establishing the link between sustainable land management, food security, and environmental balance.

An alternative focus of this study is to minimize the use of chemical inputs in farming, while promoting sustainable, resilient, and eco-friendly agricultural practices. Although advanced nano-fertilizers are already utilized in commercial agriculture, farmers often lack understanding of their compatibility with conventional chemical fertilizers. Recent studies also highlighted several challenges related to the harmful effect of excessive chemical use, which constrain the implementation of these novelties for enhancing agricultural productivity (Khaitov et al., 2020). Therefore, the primary objective of this study is to evaluate the applicability and performances of selected nano-fertilizers in combination with chemical fertilizers (NPK) on the agronomic traits of cotton under arid conditions.

2 Materials and methods

2.1 Climate characteristics

The study was carried out in Tashkent region located in the northwestern region of Uzbekistan (41.38°N, 69.46°E; 572.2 m above sea level), over the 2023–2024 growing seasons. This area experiences harsh winters, with absolute minimum temperatures recorded between −12.3 °C and −2.0 °C in December and January. Summer is extremely hot, with average temperatures ranging from 26.3 °C to 32.0 °C and peak values reaching 40.5–43.3 °C. During the vegetation periods, the accumulated effective temperatures were 2476.2 °C in 2023 and peaked at 2738.1 °C in 2024. Spring temperatures increased from 14.3 °C to 29.3 °C, which led to rapid soil desiccation and posed challenges for timely sowing operations (Figure 1).

In 2024, precipitation levels were higher than 2023, while observed indicators were 256 mm vs. 182 mm, respectively. Most of the annual precipitation occured between late autumn to mid-spring, which didn't coincide with the cotton vegetation period, resulting in minimal impact for cotton cultivation. The frequency of days exceeding 35 °C during the growing season was as follows: 71 days in 2023 and 65 in 2024. Among these, days surpassing 40 °C totaled 21 and 15, respectively. The accumulated effective temperature for the hottest period rose to 1692.8 °C in 2023-—86.6 to 98.5 °C higher than in previous years—marking the warmest growing season in the past 50 years. In autumn, temperatures began to decline from September. The transition below 10 °C occurred 22 days earlier in 2024 compared to 2023, respectively, and was accompanied by light rainfall (0.3 mm). In summary, the 2023 growing season was characterized by severe climatic conditions, with extreme heat and limited precipitation posing significant challenges to crop production.

2.2 Soil and water parameters

The cropping pattern in the study region is dominated by a cotton–winter wheat rotation system, covering approximately 85%

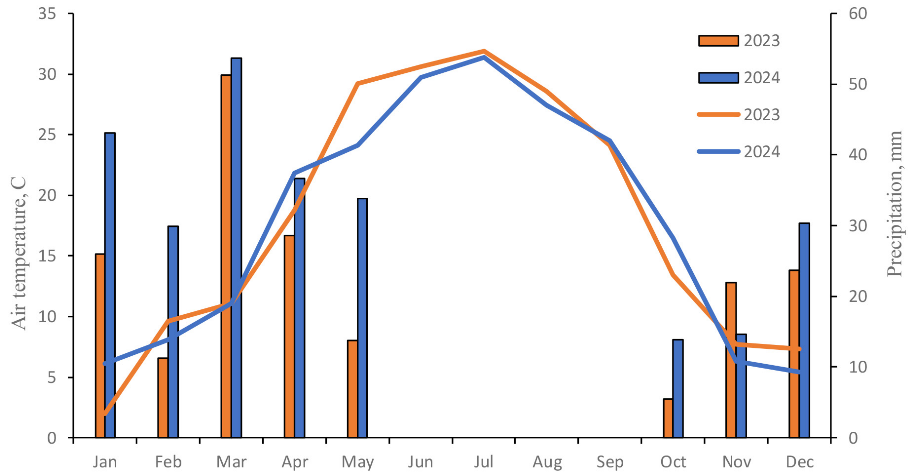

FIGURE 1
Climate data during the growing seasons of 2023 and 2024.

of the cultivated area. However, due to recent government policies, farmers have begun shifting toward the cultivation of orchards and vegetables.

The soil in the area is classified as moderately saline serosems, with electrical conductivity (EC) values ranging from 2 to 4 dS/m. Representative soil samples were collected at four depths: 0–0.15 m, 0.15–0.30 m, 0.30–0.60 m, and 0.60–1.00 m, both prior to treatment implementation (baseline) and after crop harvest. Nutrient content of soil is poor and characterized by 0.5–0.7% humus; NO_3 1.9–2.9 mg kg^{-1}, P_2O_5 11.0–16.9 mg kg^{-1}, K 246–289 mg kg^{-1} in 0–60 soil profile, even lower in 60–90 cm soil profile, consisting of 0.46% humus, NO_3 1.5 mg kg^{-1}; P_2O_5 10.3 mg kg^{-1}, and K_2O 235 mg kg^{-1} (Table 1).

The samples were air-dried and analyzed. Bulk density ranged between 1.47 and 1.56 g/cm^3 in the upper soil layers (0–30 cm). Soil pH varied from 7.75 to 8.60, indicating a moderately alkaline reaction.

Irrigation and groundwater samples were collected monthly, along with routine monitoring of groundwater levels. Drainage water used for irrigation exhibited a salinity level of ∼4,000 mg/L. Between April and September 2023, canal water salinity fluctuated between 945 and 1,331 mg/L (equivalent to 1.33–2.07 dS/m). During the same period in 2024, Sodium Adsorption Ratio (SAR) values ranged from 4.54 to 13.49, indicating a potential risk of sodicity if such water is used without proper management. Sulfate ions were the predominant anions, with $Cl^-/SO4^-$ ratios between 0.56 and 0.58, reflecting a sulfate–chloride salinity type.

Groundwater salinity ranged from 1352 to 9,416 mg/L (or 2.06–14.60 dS/m) across growing seasons. The pH values ranged from 7.85 to 8.50, maintaining a moderately alkaline profile. The dominant cations were Na^+ and Mg^+, though their concentrations varied significantly. SAR levels between 4.38 and 11.43 further characterized the water as marginal in quality, underscoring the necessity of managed irrigation techniques, particularly flood irrigation during plant establishment, to minimize upward salt movement from saline groundwater.

2.3 Experiment layout and materials

The field trial utilized a split-plot layout with three replications (Table 2). Cotton cultivars were allocated to the main plots, while fertilizer treatments were distributed within the sub-plots. Each plot occupied an area of 15.12 square meters, consisting of six ridges—each measuring 3.6 meters in length and 0.7 meters in width.

"Sila Kremniy"® is a complex silicon-based nano fertilizer containing 17–22% Si, 1–4% Fe, 0.05–0.1% Cu, and 0.05–0.1% Zn, along with S, Ca, Mg, N, P, K and other essential microelements. At a 0.05% concentration, it maintains a hydrogen index (pH) of 6.5–7.5 and has a density of no less than 1.3 g/cm^3 at 20 °C. This nano-fertilizer enhances plant immunity, stimulates metabolic and biochemical activity, and promotes growth and yield. SiO_2 strengthens cell walls, improves resistance to pests and diseases, and enhances stress tolerance.

Uzbi® is a dark brown natural nano micronized to sizes <10 µm, allowing them to enter plant leaves through stomata. Once inside, calcium carbonate reacts to release CO_2, enhancing photosynthesis and water-use efficiency. This compound controlains various bioactive compounds such as potassium and sodium humates, fulvic acids, trace elements, amino acids, enzymes, and natural organic substances as well as trace elements like Fe, Mn, Zn, and Cu support enzymatic activity and chlorophyll synthesis.

2.4 Plant nutrient analysis

Prior to harvest, cotton shoot samples were randomly collected for nutrient analysis. The samples were thoroughly rinsed with distilled water, oven-dried at 65 °C for 24 h, and subsequently ground to pass through a 0.5-mm sieve. The processed material was stored in airtight plastic bags until laboratory analysis. Nitrogen (N) content was assessed using the micro-Kjeldahl method, as outlined by Chapman and Pratt (1961). Phosphorus (P) levels

TABLE 1 Soil chemical analysis.

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

TABLE 2 Nano-application periods and norms.

Treatments	Nano treatment periods and norms		
	Seed preparation stage	Bud formation stage	Flowering stage
Control	–	–	–
Si	0.1 L/ton	0.15 L/ha	0.21 L/ha
Uzbi	1.4 L/ton	0.4 L/ha	0.6 L/ha

were measured spectrophotometrically following acid digestion, using the ascorbic acid method described by Murphy and Riley (1962). Calcium (Ca), Magnesium (Mg), and Potassium (K) were quantified from the diluted acid digestate via flame photometry. To estimate nutrient uptake (N, P, K, Ca, Mg), each concentration value was multiplied by the corresponding dry shoot weight of the cotton plants.

2.5 Nitrogen-use efficiency (NUE)

(1) *Agronomic N-Use Efficiency* (aNUE) represents the increase in crop yield per unit of N applied. It is calculated by comparing the yield from fertilized plots (Yf) to the yield from unfertilized control plots (Fageria and Baligar, 2003):

(Y0): aNUE (kg/kg) = (Yf – Y0) ÷ N applied

(2) *Physiological N-use efficiency* (pNUE) indicates how efficiently the plant converts absorbed N into additional yield (Isfan, 1990):

pNPE (kg kg^{-1}) = $(Y_f - Y_0)/(TNU_f - TNU_0)$

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

(3) *Internal N-use efficiency* (iNUE) iNUE quantifies the yield produced per unit of N concentration in plant tissue (Witt et al., 1999):

iNUE (g g^{-1}) = Cotton yield/Tissue N concentration.

(4) *Apparent N recovery efficiency* (aNRE) measures the proportion of applied N that was actually absorbed by the plants, expressed as a percentage (Dilz, 1988):

aNRE (%) = $[(TNU_f - TNU_0)/\text{N applied}] \times 100$

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

2.6 Statistic analysis

The CropStat program (CropStat, 2015) (ANOVA statistical system) was employed to assess the impact of nano applications on cotton growth, yield and nutrient uptake parameters. Significant differences among treatment means were identified using the Least Significant Difference (LSD) method. The effects of two distinct nanofertilizers (Si and Uzbi) under three fertilizer regimes (N_{150} P_{105} K_{75}; $N_{200}P_{140}$ K_{100}; $N_{250}P_{175}K_{125}$) on cotton's vegetative and reproductive traits were analyzed using statistical comparisons at a 5% significance level ($p = 0.05$), based on data from three experimental replications.

3 Results

3.1 Cotton yield

The application of nano-treatments substantially enhanced cotton biomass yield, total economic yield, and seed weight parameters across the three fertilizer regimes ($N_{150}P_{105}K_{75}$, $N_{200}P_{140}K_{100}$, and $N_{250}P_{175}K_{125}$) (Table 3). Si based nano-treatment consistently performed well to increase cotton yield parameters and the Uzbi treatment in enhancing overall crop performance.

Especially Si nano treatment significantly increased cotton yield by 31.3% (total yield 3,927 kg/ha and additional cotton yield +937 kg/ha) under the $N_{150}P_{105}K_{75}$ fertilizer regime over the control and tended to decrease slightly with the increase of fertilizer rates. The highest seed weight (126.4 g) was also achieved under the Si treatment in combination with the $N_{150}P_{105}K_{75}$ fertilizer regime. The measured yield parameters slightly decreased with increasing chemical fertilizer rates, except biomass yield. Uzbi also showed improved results compared to the control, exhibiting the highest yield metrics (3,776 kg/ha) and seed weight (125.9 g/1,000 seeds) with the moderate fertilizer norms ($N_{200}P_{140}$ K_{100}), albeit less pronounced than Si.

At the moderate fertilizer level ($N_{200}P_{140}K_{100}$), the Uzbi treatment exhibited high efficacy, enhancing total cotton biomass by 12.9% and total yield by 26.3% compared to the control group values. The seed weight also significantly increased (125.9 g) relative to the lower fertilizer regime.

Under the high-input $N_{250}P_{175}K_{125}$ regime, Si continued to deliver more yields (3,868 kg/ha) and an additional cotton gain of +878 kg/ha compared to the control, although biomass output and cotton yield appeared to plateau. Likewise, the cotton biomass and yield parameters increased by 13.0 and 22.9%, against the control variables, respectively, after the Uzbi treatment.

Statistical analysis ($p < 0.05$) confirmed that treatment effects were significant across most parameters, with Si frequently associated with superior values. As this study presented that cotton yield data further supported the advantage of nano in relation to

TABLE 3 Total biomass, vegetative mass, and economic yield (Averaged across 2023 and 2024 growing seasons).

Chemical fertilizers norms, kg/ha	Nano-treatment	Biomass yield, kg/ha	Total yield, kg/ha	Additional cotton yield, kg/ha	Weight of 1,000 seeds, g
N_{150} P_{105} K_{75}	Control	7475d	2990d	–	120.2d
	Si	8217c	3927a	937	126.4a
	Uzbi	8125c	3371c	381	125.2ab
$N_{200}P_{140}$ K_{100}	Control	8155c	3386c	396	122.5c
	Si	8398b	3879a	889	126.3a
	Uzbi	8440b	3776ab	786	125.9ab
$N_{250}P_{175}K_{125}$	Control	8758a	3512bc	522	124.7b
	Si	8379b	3868a	878	126.3a
	Uzbi	8450b	3675b	685	125.5ab

Means separated by same lower case letter (a to d) in each column were not significantly different among treatments at $p \leq 0.05$.

TABLE 4 Growth variables of cotton (Averaged across 2023 and 2024 growing seasons).

Chemical fertilizers norms, kg/ha	Nano-treatment	Germination, %	Fusarium Wilt, %	
			1.08	1.09
N_{150} P_{105} K_{75}	Control	43.4c	4.1a	6.3a
	Si	72.5a	1.9c	3.8c
	Uzbi	58.3b	1.8c	3.5c
$N_{200}P_{140}$ K_{100}	Control	43.9c	3.1b	5.2b
	Si	66.7b	1.8c	3.6c
	Uzbi	72.2a	1.9c	2.3d
$N_{250}P_{175}K_{125}$	Control	45.4c	3.5ab	6.6a
	Si	71.3a	1.9c	3.5c
	Uzbi	57.8b	2.1c	3.2c

Means separated by same lower case letter (a to e) in each column were not significantly different among treatments at $p < 0.05$.

chemical fertilizers. The application of Si nano-fertilizer reduced the volume of chemical nutrition by 50%, while Uzbi by 30–35%. These findings underscore the potential of silicon-based nano-treatments to enhance cotton productivity and quality, even in low-fertilizer environments.

The cotton treated with Uzbi 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.

The study assessed yield components of cotton under the synergetic effect of nano and chemical fertilizers offers promising advancements by enabling precise delivery of nutrients. The positive effects were more pronounced with the Si treatment, suggesting Si is highly effective even under reduced nutrient input. Applying the Uzbi nanoproduct indicated its potential as an alternative nutrient treatment.

3.2 Cotton growth and stress tolerance under nano impact

The effects of nano-treatment and fertilizer regimes on early-stage cotton growth stages, including germination rate and disease incidence were evaluated across the 2023 and 2024 growing seasons (Table 4). Notable differences emerged in plant vigor and disease resistance, particularly in response to Si-based treatments.

Germination percentage varied significantly across treatments. Under the $N_{150}P_{105}K_{75}$ regime, Si nano treatment resulted in the highest germination rate (72.5%), followed by Uzbi (58.3%), while the control group lagged markedly at 43.4%. Similar trends persisted across higher fertilizer inputs: Si maintained elevated germination levels at both $N_{200}P_{140}K_{100}$ (66.7%) and $N_{250}P_{175}K_{125}$ (71.3%), compared to the control (43.9% and 45.4%, respectively). The Uzbi treatment consistently promoted germination above control levels, albeit slightly lower than Si.

Fusarium wilt incidence was notably reduced in nano-treated plants. The control plots displayed the highest disease prevalence, particularly under the $N_{250}P_{175}K_{125}$ regime (4.1%). Si and Uzbi treatments markedly suppressed wilt incidence across all fertilizer levels, with Uzbi exhibiting the lowest values-—1.8%, 1.9%, and 2.1% at low, medium, and high fertilizer rates, respectively. The data suggests that Uzbi may possess stronger antifungal properties during early growth stages than Si.

When disease incidence was monitored during the flowering-fruit formation stage of cotton (in August), a consistent advantage of Si treatment was observed. Across all fertilizer regimes, Si treatment effectively suppressed disease spread with values such as 3.8% under $N_{150}P_{105}K_{75}$, compared to 6.3% in the control.

The minimum disease level was observed under the synergistic effect of Uzbi with $N_{200}P_{140}$ K_{100}, while Uzbi substantially improved disease control, outperforming in most conditions.

Statistical analysis indicated significant differences among treatments ($p < 0.05$), with letter-based groupings validating the efficacy of nano-treatments. The observed improvements in germination and disease resistance underscore the potential of Si and Uzbi nano-formulations to strengthen crop resilience and reduce early-stage biotic stress in cotton cultivation.

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 2023 and 2024 growing seasons).

Chemical fertilizers norms, kg/ha	Nano-treatment	N	P	K (%)	Ca	Mg
N_{150} P_{105} K_{75}	Control	2.11c	0.25c	0.28c	0.43c	0.14c
	Si	3.53a	0.53a	0.36a	0.57a	0.16a
	Uzbi	2.96b	0.46b	0.31b	0.49b	0.15b
$N_{200}P_{140}$ K_{100}	Control	2.57b	0.45a	0.31b	0.49b	0.17b
	Si	3.45a	0.57b	0.36a	0.56a	0.18a
	Uzbi	3.43a	0.51a	0.35a	0.54a	0.15a
$N_{250}P_{175}K_{125}$	Control	2.90b	0.44b	0.32b	0.51b	0.14b
	Si	3.43a	0.53a	0.36a	0.56a	0.16a
	Uzbi	3.38a	0.48a	0.34a	0.53b	0.17a

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

3.3 Nutrient uptake and efficiency in cotton under nano-fertilization

The application of nano fertilizers significantly influenced cotton's nutrient concentration, total nutrient uptake, and nitrogen-use efficiency (NUE) under arid and continental climate conditions over two consecutive growing seasons (2023–2024). Cotton shoot N, P, Ca and Mg status were enhanced significantly after the application of nano fertilizers (Si and Uzbi). At the same time, the impact of the higher chemical fertilizer regime ($N_{250}P_{175}K_{125}$) was considerably prominent than that of the lower fertilizer regime (Table 5). The total N concentration increased by 67.1% compared to the control value when the Si nano treatment was used with the $N_{150}P_{105}K_{75}$ regime. Similarly, P, K, Ca and Mg concentrations of cotton shoots were greater by 2.12-fold, 28.6%, 32.6% and 14.3% than the control values when the Si nano treatment interacted with the $N_{150}P_{105}K_{75}$ regime.

Similarly, Uzbi consistently enhanced the concentrations of N, P, K, Ca, and Mg in cotton shoots across all fertilizer levels. The highest values were recorded with Si under $N_{150}P_{105}K_{75}$, reaching 3.53% for N and P, 0.36% for K and Mg, and 0.57% for Ca. Uzbi also elevated nutrient levels compared to control, although slightly lower than Si. This suggests that both nano treatments boost nutrient assimilation in plant tissue, improving physiological processes under arid stress.

As the results in Table 6 showed, Si treatments resulted in the most pronounced increases in total nutrient uptake (kg/ha), especially for N and P. Under $N_{150}P_{105}K_{75}$, N uptake jumped from 86.6 kg/ha in control to 140.7 kg/ha with Si. Similar trends were observed across medium and high fertilizer rates, where Si maintained superiority in all nutrient uptakes.

Similarly, N uptake varied significantly following the Uzbi treatments across the applied chemical fertilization regimes, while the mean value ranged from 121.4 to 138.8 kg ha^{-1}. The highest N uptake was observed in the Uzbi × $N_{200}P_{140}$ K_{100} interaction. Also, applying the Uzbi nano treatment led to a significant increase in total N, P, K, Ca and Mg uptake by cotton.

Likewise, with the Si treatment, the maximum P uptake reached 30.11 kg ha^{-1} under the $N_{150}P_{105}$ K_{75} regime, while the minimum value was 22.92 kg ha^{-1} for the control group. When Uzbi was applied, K and Ca uptake parameters were significantly higher in relations to the without nano treatment in all tested chemical fertilizer regimes. The uptake of total K and Ca increased significantly by 27.5 and 26.3%, respectively compared to the control indices. Despite some positive effects, Mg uptake did not show a significant change with the nano-nutrition treatments. On the other hand, Ca uptake increased substantially following nano-nutrition application. These findings suggest Uzbi nano treatments amplify nutrient mobilization and root absorption under field conditions.

As anticipated, applying foliar Si nano-nutrition stimulated plant growth, which in turn heightened the demand for essential nutrients. The marked increase in N, P, and K uptake observed in cotton treated with Si is likely due to enhanced nutrient balance and improved nutrient adsorption. Overall, the absorption of nitrogen (N), phosphorus (P), and potassium (K) was notably greater with the Si treatment compared to the use of Uzbi.

The effects of the nano fertilizers in combination with the chemical fertilizer norms on the NUE indices were found to be significant at $p < 0.05$ level in all measured parameters and letters assigned to means confirmed differences among nano treatments (Table 7). The synergetic effect on the observed NUE metrics was substantially greater with the Si application. Agronomic NUE (aNUE) more than doubled with Si, from 3.27 (control) to 9.51 under low fertilizer input. Apparent nitrogen recovery efficiency (aNRE) considerably enhanced from 14.4% in control vs. 43.1% with Si at $N_{150}P_{105}K_{75}$. Physiological NUE (pNUE) and internal NUE (iNUE) were also optimized, indicating better conversion and utilization of absorbed nitrogen.

Uzbi also improved NUE values, although less efficiently than Si. The effect of Uzbi was significantly higher than the control group in all tested combinations of chemical fertilizer regimes. The highest indicators of Uzbi were observed at $N_{200}P_{140}K_{100}$ possible plateau effects, aNUE, pNUE, iNUE, and aNRE parameters were increased by 2.6-fold, 1.9-fold, 19.2% and 2.1-fold, respectively compared to control.

NUE refers to the proportion of N absorbed by the plant relative to the total amount of N fertilizer applied. Interestingly,

TABLE 6 Effects of nano fertilization on total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) uptake by irrigated cotton under controlinental climate (Averaged across 2023 and 2024 growing seasons).

Chemical fertilizers norms, kg/ha	Nano-treatment	N	P	K (kg/ha)	Ca	Mg
N_{150} P_{105} K_{75}	Control	86.6d	22.92c	53.82d	17.19	5.19
	Si	140.7a	30.11a	65.69b	22.58	5.50
	Uzbi	121.4b	25.84b	60.68c	19.38	5.29
$N_{200}P_{140}$ K_{100}	Control	105.5c	25.96b	60.95c	19.47	5.24
	Si	141.7a	29.74a	69.82a	22.30	5.43
	Uzbi	140.8a	28.95a	67.97b	21.91	5.72
$N_{250}P_{175}K_{125}$	Control	118.9b	26.93b	63.22c	20.19	5.32
	Si	140.9a	29.65a	69.62a	22.24	5.42
	Uzbi	138.8a	28.18a	66.15b	21.13	5.15

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

TABLE 7 Effects of nitrogen fertilization with nano fertilizers on nitrogen-use efficiency of irrigated cotton under controlinental climate (Averaged across 2023 and 2024 growing seasons).

Chemical fertilizers norms, kg/ha	Nano-treatment	aNUE (kg kg^{-1}) _	pNUE (g g^{-1})	iNUE (%)	aNRE
N_{150} P_{105} K_{75}	Control	3.27d	7.6e	10.17d	14.4d
	Si	9.51a	15.9a	14.14a	43.1a
	Uzbi	5.81c	11.4d	11.40c	27.6b
$N_{200}P_{140}$ K_{100}	Control	5.91c	11.1d	11.17c	12.8d
	Si	9.19a	15.9a	11.24c	30.9b
	Uzbi	8.51a	14.4b	12.12b	30.4b
$N_{250}P_{175}K_{125}$	Control	6.75b	13.7c	11.01c	15.6d
	Si	9.12a	15.9a	11.27c	24.4c
	Uzbi	7.83b	13.2c	11.97c	23.5c

Means exhibited by lowercase letters (a to 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; aNRE, Apparent nitrogen recovery efficiency.

Si's enhancements were most evident at the lower fertilizer regime ($N_{150}P_{105}K_{75}$), hinting at higher NUE. Enhancing NUE is crucial for promoting sustainable agricultural practices, especially in efforts to boost cotton yield. In this study, NUE indicators were notably higher following the application of Si treatment compared to Uzbi, leading to a significantly greater yield per unit of N fertilizer used.

Nano fertilization, particularly with Si presents a promising strategy for improving nutrient dynamics and NUE in cotton grown under climatic stress. By optimizing both shoot nutrient concentrations and root-level uptake, these treatments may lead to more sustainable and productive cotton systems.

4 Discussion

4.1 Cotton performance with nano fertilizers

The results of this study demonstrate that nano fertilization, particularly the Si formulation can significantly enhance nutrient accumulation, uptake, and NUE in cotton grown under challenging arid climates. Consistent performance improvements across fertilizer regimes highlight the potential of nano-enabled fertilization to optimize cotton productivity and sustainability. Applying nanofertilizers in combination with appropriate mineral fertilizer rates is essential for enhancing crop productivity, building plant resilience to stress factors, and protecting food, land, and water systems. Adequate nutrient supply enables well-functioning metabolic processes that are crucial for maintaining nutrient balance and plant performance. This study showed that cotton likely did not experience nutrient stress at any developmental stage, as nano fertilizers were applied alongside chemical fertilizers according to recommended guidelines. Consequently, nano-treated plants exhibited increased partitioning and diversion of assimilates from vegetative development toward reproductive growth, resulting in higher yield (Table 3). In contrast, under conventional practices (control), cotton accumulated more biomass but showed less efficient assimilate allocation to generative organs. Several studies have also pointed out that nano applications positively influence the reproductive development of crops (Arifur Rahman et al., 2024).

To withstand biotic and abiotic stresses, including the damaging impacts of salinity and drought, crops require an optimal balance of macro- and micronutrients (Kumar et al., 2021). Proper nutrient management can improve a plant's ability to endure drought by sustaining or enhancing water use efficiency and resilience to climate variability (Nurbekov et al., 2025). As turned out, Si nanoparticles enhance plant resistance to diseases and pests by boosting physiological endurance and exhibiting phytoprotective properties. Consistent with the findings of this study, El-Ramady et al. (2022) reported that nano-Si application improved photosynthetic efficiency, maintained nutrient equilibrium, reduced leaf water loss, and increased water uptake through the roots. Valizadeh and Milic (2016) further observed that silicon enhances both antioxidant and non-antioxidant enzyme activity, helping protect plants from oxidative damage induced by salinity. Moreover, Si plays a role in regulating osmotic processes, which supports the function of photosynthetic enzymes.

Recent research has shown that Si nanotreatment can reduce salt accumulation in both roots and shoots when plants are exposed to stress conditions such as salinity and drought (Awad-Allah, 2023). These researchers also noted that Si enhances root hydraulic conductivity and promotes root development, thereby improving water uptake and increasing leaf water content. These findings underscore the need for further interdisciplinary studies to explore the potential of nano-Si in mitigating the adverse effects of salt and drought stress (Toderich et al., 2020). Si nano compounds possess hygroscopic properties that allow a single Si atom to bind approximately 100–140 water molecules, thus reducing dehydration and improving drought tolerance. In arid regions, these properties enhance moisture retention, facilitate salt breakdown, and improve soil structure, contributing to better aeration and water infiltration.

From an agronomic perspective, current evidence supports nano-fertilization as a promising approach to enhance nutrient use efficiency while minimizing input waste. Nano-fertilizers have demonstrated the potential to reduce greenhouse gas emissions and decrease reliance on conventional mineral fertilizers by up to 50% in this study, highlighting their superior efficiency compared to traditional formulations (Rajemahadik et al., 2018).

Conventional fertilizers are a major contributor to greenhouse gas emissions and environmental degradation (Arifur Rahman et al., 2024). In contrast, nano-fertilizers function more efficienty andapplied nanoscale particles target nutrient delivery precisely. Nanoparticles penetrate plant tissue more effectively, thereby increasing nutrition efficacy by higher plant uptake with lower chemical fertilizer application rates. These particles bind to key transport pathways, ensuring direct nutrient uptake by plants and significantly reducing ecological harm. However, the effectiveness of nano-fertilizers is highly dependent on the specific crop or plant species, underscoring the need for tailored applications (Jakhar et al., 2022). Therefore, integrating nanotechnology with agrochemical strategies represents a pivotal advancement toward sustainable agriculture and resilient food systems.

4.2 Nano treatments enhance nutrient uptake and NUE

A key metric of NUE, internal NUE (iNUE), reflects how effectively plants absorb and utilize applied N to convert soil nutrients into economic yield. Enhancing iNUE is vital for improving crop quality and productivity while minimizing environmental harm (Kah et al., 2018). The integration of nanonutrition into the nutrient management program led to optimized NUE, higher crop yields and enhanced the efficiency of chemical fertilizers. Consistent with this study, most nano compounds contain a range of physiologically active composites, including macro- and micronutrients, vitamins, and growth regulators (El-Desouky et al., 2021). The Si based fertilizer *Sila kremniy*®, used in this study, contains essential nutrients such as N, Ca, Bo, Mg, Fe, Zn, Mn, Mo, and other trace elements that are critical for plant growth in depleted agricultural lands caused by years of intensive cultivation.

The nano-Si played a notable role in supporting nutrient status in cotton, as reflected in the improved nutrient uptake under water-limited conditions. The application of the Si nano treatment notably increased shoot concentrations of N, P, K, Ca, and Mg across all fertilizer regimes. For instance, Si application enhanced N and P concentrations by 67% and 2.1-fold, respectively at the N_{150} P_{105} K_{75} regime. This marked elevation in macronutrients suggests that Si nano-compound enhances nutrient assimilation, possibly by increasing root surface area and facilitating translocation mechanisms. Uzbi treatments also led to statistically significant improvements, although slightly less pronounced than Si, implying variability in nano carrier efficacy. These improvements may be attributed to increased biomass and crop yield parameters (Table 3) and enhanced nutrient absorption efficiency (Table 5).

The impact on total nutrient uptake was substantial with the Si application, especially in low-input regimes (Table 6). Under $N_{150}P_{105}K_{75}$, N uptake increased by 67% with Si compared to the control, reaching 144.7 kg/ha vs. 86.6 kg/ha. Notably, similar benefits were observed across medium and high input levels, indicating the robustness of nano treatments under varying nutrient loads. This finding aligns with previous reports suggesting that nanomaterials can facilitate better root-soil interface interactions, thereby enhancing mass flow and diffusion of nutrients (Iqbal et al., 2019). These results indicate that nano-fertilizers can increase nutrient status in cotton plants, which positively influences vegetative growth, reproductive development, and overall yield and quality. Recent research indicated that foliar application of silicon enhances the effectiveness of both macro- and micronutrients such as i.e., N, P, K, Ca, Fe, Mn, Cu, and Zn (Khaitov et al., 2024). As noted by Barzana et al. (2022), the assimilation of these micronutrients in plants is intricately connected due to their roles in protein synthesis. Improved nutrient uptake through nanonutrition has been shown to significantly boost crop yields (Zia-Ur-Rehman et al., 2023), offering a promising strategy for sustainable agriculture by increasing N use efficiency while conserving essential water and nutrient resources.

As this study revealed all four NUE indices—agronomic (aNUE), physiological (pNUE), internal (iNUE), and apparent recovery efficiency (aNRE) were significantly enhanced by the nano treatments (Table 7). Under low nutrient conditions, aNUE nearly tripled with Si (9.51 vs. 3.27 kg/kg in control), and aNRE increased from 4.4% to an exceptional 43.1%, implying that nano Si maximizes the conversion of applied N into harvestable biomass. These improvements were sustained under higher input levels, although efficiency gains slightly plateaued, suggesting a diminishing return at very high fertilizer rates. Uzbi also yielded considerable improvements, particularly in pNUE and iNUE, demonstrating its utility as a supplementary nano fertilizer.

The enhanced efficiency of nano-Si may be attributed to its role in strengthening root development, enhancing enzymatic activity, and improving nutrient transport mechanisms. Recent experiments also have demonstrated that Si nano treatments enhance photosynthetic activity, reduce leaf water loss, improve root water uptake, and support nutritional balance in plants (Jaganathan and Godin, 2012). Additionally, Si application stimulates both antioxidant and non-antioxidant enzyme activity, helping mitigate oxidative damage caused by salinity and contributing to osmotic regulation, which further promotes photosynthetic enzyme function (Roychoudhury, 2020). Studies also report that Si reduces salt accumulation in roots and shoots, thereby increasing crop tolerance to salinity (Gangwar et al., 2023). Moreover, Si has been shown to improve drought resistance by regulating transpiration, stomatal conductance, and leaf relative water content (Liu et al., 2021).

As shown in this study, the measured yield and NUE parameters decreased with chemical fertilizers rates increased, implying the nano compounds are efficient in terms of NUE and may help to avoid excessive chemicals. The use of nano fertilizers has potential to reduce reliance on chemical inputs and represents a viable strategy for sustainable agriculture, particularly under challenging environmental conditions (Astaneh et al., 2018). In contrast, the widespread use of chemical fertilizers and pesticides has already shown significant risks to ecosystems, biodiversity, and human health (Zhou et al., 2025). In line with this study, recent publications have also asserted that crop nano-nutrition strategies contribute to climate-smart agriculture by preserving natural resources and supporting ecosystem functions (de Moraes and Lacava, 2022). These nano-nutrients play a crucial role in sustaining the global food supply, although they are expected to become increasingly important in future agricultural practices.

4.3 Agronomic and environmental implications

The emergence of novel nanomaterials through ongoing nanotechnology research offers new opportunities for sustainable crop production, particularly under challenging environmental conditions. The application of nano-fertilizers improved nutrient uptake and utilization efficiency which in turn led to increased yields with reduced fertilizer input. These nano particles not only mitigate environmental risks by reducing nutrient leaching and volatilization, but also play a pivotal role in improving soil health by preventing degradation caused by excessive fertilizer use. Furthermore, the tested nanoparticles in this study acted as antimicrobial agents against plant pathogens, enhanced both biotic and abiotic resilience in cotton plants. In agreement with this study, Morab et al. (2021) declared that nanocarriers presents transformative opportunities for crop production by improving nutrient use efficiency, enhancing pest control, and enabling precision agriculture. The development of eco-friendly biodegradable nanomaterials ensures crop production sustainability by ensuring precise nutrient delivery, proactive disease and stress management, minimizing the application of chemical fertilizers and pesticides. While challenges exist, continued research and regulatory advancements will pave the way for large-scale adoption, contributing to sustainable and resilient agricultural systems.

Nano-fertilizers offer a multifaceted solution for stimulating plant growth, enhancing secondary metabolite synthesis, and bolstering resistance to biotic stressors—highlighting their emerging significance as integral tools in sustainable and precision agriculture (Elemike et al., 2019; Khater et al., 2022).

This manuscript also aimed to explore the potential integration of nanotechnology into crop production systems, based on the assumption that nano fertilizers improve nutrient uptake efficiency, accelerate root development, control plant diseases and optimize plant physiological activity. These functionalities stem from the unique properties of nanoparticles, including their high surface area-to-volume ratio, enhanced solubility, and efficient targeting capabilities attributes linked to their small size, rapid mobility, and minimal toxicity (Elabd, 2020).

Agriculture remains an innovation hub where science meets production to discover solutions for food security and climate challenges, strengthen resilience against environmental stresses and promote sustainable farming systems. The next step should focus on enhancing the efficiency of nano-formulations and developing a universal product applicable across a wide range of crops with an emphasis on transforming agricultural systems toward sustainable development.

In sum, nano fertilization especially with Si, offers a promising route toward higher efficiency and climate-smart cotton farming. Future research should explore the long-term effects of nano treatment in combination with chemical fertilizers, assess their impact on soil health, and investigate potential synergies with biological or chemical stimulants as well as precision irrigation technologies.

5 Conclusion

As this study showed, the application of nano compounds in combination with chemical fertilizers had a consistent synergistic effect on cotton nutrition, growth and yield quality parameters under arid conditions, effectively alleviating the negative impacts of abiotic and biotic stresses. The effect of Si-nano treatment was more pronounced at $N_{150}P_{105}K_{75}$, by improving N-use efficiency of cotton by 25–45% and cotton yield by 25% relative to the control. Whereas, Uzbi exhibited the best generative traits at $N_{200}P_{140}$ K_{100} by improving nutrient use efficiency and enhancing cotton yield. Thus, it may be more cost-effective and desirable to apply chemical fertilizers at a rate of $N_{150}P_{105}K_{75}$ in combination with the Si nano compound for irrigated cotton production under arid climatic conditions of Uzbekistan.

This study lays the groundwork for future investigations into the applicability of nano-fertilizers in enhancing nutrient efficacy and crop productivity, thereby reducing dependence on chemical fertilizer. Future research should focus on uncovering the mechanisms underlying their positive interactions, leading to innovative agricultural strategies that prioritize both yield optimization and resource efficiency.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

II: Formal analysis, Project administration, Validation, Writing – original draft, Writing – review & editing. OS: Funding acquisition, Software, Writing – original draft, Writing – review & editing. SS: Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing. KhK: Investigation, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. SB: Data curation, Software, Writing – original draft, Writing – review & editing. IB: Resources, Visualization, Writing – original draft, Writing – review & editing. KI: Formal analysis, Validation, Writing – original draft, Writing – review & editing. BU: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. OK: Formal analysis, Resources, Validation, Writing – original draft, Writing – review & editing. DTun: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. DTur: Methodology, Software, Writing – original draft, Writing – review & editing. KoK: Data curation, Methodology, Writing – original draft, Writing – review & editing. MK: Investigation, Methodology, Writing – original draft, Writing – review & editing. RK: Investigation, Software, Writing – original draft, Writing – review & editing. BK: Conceptualization, Investigation, Software, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

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.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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