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Effect of foliar application of nano titanium dioxide and nano silicon dioxide on growth, yield, quality, postharvest behavior, and economics of okra (*Abelmoschus esculentus* L.)

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Abstract

This study evaluated the foliar application of nano titanium dioxide (Nano-TiO₂) and nano silicon dioxide (Nano-SiO₂) on growth, yield, quality, postharvest behavior, and economics of okra during the summer season of 2025 at the Central Horticulture Research Farm, SHUATS, Prayagraj, India. Sixteen treatment combinations were formed from four TiO₂ levels (0, 50, 75, and 100 ppm) and four SiO₂ levels (0, 50, 75, and 100 ppm) and tested in a factorial randomized block design with three replications. Foliar sprays were applied at 30 days after sowing and repeated at 15-day intervals. The combined nano-foliar treatments significantly improved vegetative growth, chlorophyll status, earliness, reproductive attributes, pod quality, and economic returns over the control. T₁₃ (100 ppm TiO₂ + 50 ppm SiO₂) produced the maximum plant height at 60 and 90 DAS (14.46 and 34.99 cm), T₅ (50 ppm TiO₂ + 50 ppm SiO₂) recorded the highest pods per plant (27.78) and average pod weight (14.57 g), while T₁₅ (100 ppm TiO₂ + 100 ppm SiO₂) gave the highest pod yield (12.62 t ha⁻¹), net return (₹164,288 ha⁻¹), and benefit:cost ratio (2.86). The results demonstrate a strong synergistic effect between Nano-TiO₂ and Nano-SiO₂ and support the use of T₁₅ for maximizing okra productivity and profitability under Prayagraj agro-climatic conditions.

Keywords: Okra, nano titanium dioxide, nano silicon dioxide, foliar spray, growth, yield, quality, postharvest, economics, factorial randomized block design

1. Introduction

Okra (*Abelmoschus esculentus* L.) is an economically important vegetable crop in tropical and subtropical agriculture because of its nutritional value, culinary utility, and income-generating potential for growers. Improving its productivity while preserving input efficiency is therefore a major agronomic objective in vegetable science [2, 6, 16].

Conventional fertilizer use alone often suffers from low nutrient-use efficiency and greater environmental loss, which has encouraged the development of nanotechnology-based nutrient delivery systems in agriculture [2, 10, 11, 12, 16]. Nanomaterials used as foliar inputs can improve nutrient availability, uptake dynamics, and physiological activity while requiring relatively smaller quantities than bulk formulations [5, 6, 11, 18].

Among nanomaterials, Nano-TiO₂ has been associated with better chlorophyll synthesis, improved light harvesting, enhanced photosynthetic activity, and stimulation of enzyme systems involved in growth and biomass production [1, 3, 4, 7, 17, 19, 20]. Likewise, Nano-SiO₂ has been reported to strengthen plant tissues, improve stress tolerance, support water-use efficiency, and contribute to better crop productivity and physiological balance [8, 9, 13, 14, 15].

The practical advantage of foliar delivery lies in faster plant response and reduced reliance on soil-mediated nutrient transformation. For vegetable crops, such precision-input approaches are particularly relevant where short crop duration requires rapid nutrient assimilation and sustained canopy performance [5, 10, 11, 12].

Although earlier work has shown the promise of TiO₂ and silicon-based nanoparticles in crops, limited field evidence exists on their combined foliar use in okra under the agro-climatic conditions of Prayagraj. The present study was therefore undertaken to examine their interaction effects on growth, yield, quality, postharvest behavior, and economics, and

to identify an optimum combination for field recommendation [8, 9, 17, 20].

2. Materials and Methods

2.1 Experimental Site, Weather, and Soil

The field experiment was carried out from 25 March to 15 June 2025 at the Central Horticulture Research Farm, Department of Horticulture, Naini Agricultural Institute, SHUATS, Prayagraj (25.57° N latitude, 81.50° E longitude, 98 m above mean sea level). The crop season experienced hot subtropical summer conditions with maximum temperature ranging from 33.2 to 43.6 °C and relative humidity ranging from 27 to 42%.

The experimental field had sandy loam soil with 60% sand, 24% silt, and 14.49% clay. The soil pH was 7.2, EC was 0.15 dS m⁻¹, organic carbon was 0.4%, and available N, P, and K were 250, 135, and 344 kg ha⁻¹, respectively.

2.2 Crop, Design, and Treatments

The okra hybrid Super Kranthi was used as the experimental crop. The trial was laid out in a 4 × 4 factorial randomized block design with three replications. Four concentrations of Nano-TiO₂ (0, 50, 75, and 100 ppm) and four concentrations of Nano-SiO₂ (0, 50, 75, and 100 ppm) generated sixteen treatment combinations (T₀ to T₁₅). The crop was raised at 60 cm × 30 cm spacing in 2 m × 2 m plots. Foliar sprays were applied at 30 DAS and repeated at 15-day intervals. Standard agronomic practices, irrigation, weeding, and plant protection were followed uniformly

across treatments.

2.3 Traits Recorded and Statistical Analysis

Growth traits included plant height, leaves per plant, branches per plant, stem girth, leaf area index (LAI), and total chlorophyll content. Yield traits included days to first flowering, pods per plant, days to first marketable harvest, pod length, pod diameter, average pod weight, pod weight per plant, and pod yield per hectare. Quality traits included fiber content, pH, and TSS. Postharvest traits included firmness and physiological loss in weight.

The data were subjected to ANOVA appropriate to factorial randomized block design. The significance of factors A (Nano-TiO₂), B (Nano-SiO₂), and A × B interaction was tested at the 5% level using the F-test. Critical difference (CD) and standard error of difference [SE(d)] were used for mean comparison. Based on the thesis results, most major growth, yield, and quality variables showed statistically significant treatment effects, with pH interaction being non-significant.

3. Results

3.1 Selected Growth and Physiological Responses

The thesis demonstrated that Nano-TiO₂ and Nano-SiO₂ significantly improved vegetative performance over the control. Table I summarizes the best treatment combinations for major growth and physiological traits retained in this research-paper version.

Table 1: Selected Growth and Physiological Responses of Okra under Nano-TiO₂ and Nano-SiO₂ Treatments

Trait	Best treatment	Value	Inference
Plant height at 30 DAS	T ₁₀ (75 ppm TiO ₂ + 75 ppm SiO ₂)	6.71 cm	Maximum early vigor
Plant height at 60 DAS	T ₁₃ (100 ppm TiO ₂ + 50 ppm SiO ₂)	14.46 cm	Best mid-stage growth
Plant height at 90 DAS	T ₁₃ (100 ppm TiO ₂ + 50 ppm SiO ₂)	34.99 cm	Tallest plants at harvest stage
Leaves at 60 DAS	T ₁₅ (100 ppm TiO ₂ + 100 ppm SiO ₂)	12.60 plant ⁻¹	Highest leaf production
Leaves at 90 DAS	T ₁₀ (75 ppm TiO ₂ + 75 ppm SiO ₂)	25.60 plant ⁻¹	Best foliage retention
Leaf area index at 90 DAS	T ₁₅ (100 ppm TiO ₂ + 100 ppm SiO ₂)	4.40	Largest assimilatory canopy
Chlorophyll at 90 DAS	T ₁₂ (100 ppm TiO ₂ + 0 ppm SiO ₂)	47.73 SPAD	Highest photosynthetic status

Plant height progression of selected treatments is further illustrated in Fig. 1. T₁₃ and T₁₅ consistently outperformed the control across stages, while T₁₀ showed superior early-

stage response and maintained strong later-stage performance.

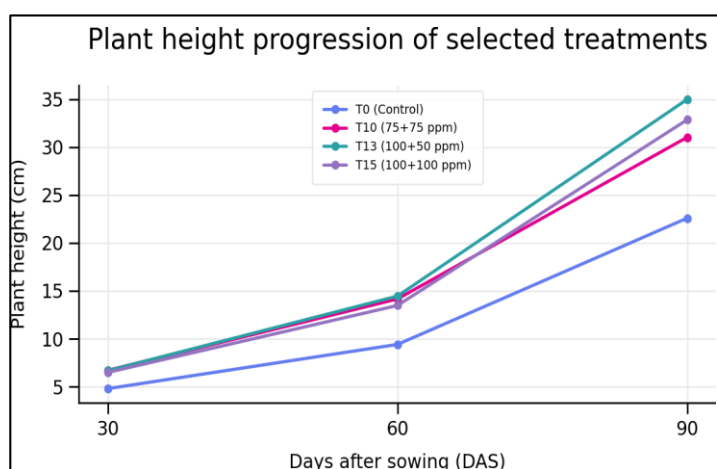


Fig 1: Plant height progression of selected okra treatments at 30, 60, and 90 DAS.

3.2 Yield, Quality, and Economic Responses

Yield, pod quality, and economics were markedly altered by treatment combination. Table II presents selected thesis-

derived yield, quality, and economic results that are most relevant for journal presentation.

Table 2: Selected Yield, Quality, and Economic Responses of Okra under Nano-TiO₂ and Nano-SiO₂ Treatments

Trait	Best treatment	Value	Remark
Earliest flowering	T ₉ (75 ppm TiO ₂ + 50 ppm SiO ₂)	40.60 days	Fastest reproductive initiation
Pods per plant	T ₅ (50 ppm TiO ₂ + 50 ppm SiO ₂)	27.78	Highest pod number
Earliest marketable harvest	T ₁ (0 ppm TiO ₂ + 50 ppm SiO ₂)	51.00 days	Earliest picking
Pod length	T ₁₃ (100 ppm TiO ₂ + 50 ppm SiO ₂)	12.82 cm	Longest pods
Pod diameter	T ₈ (75 ppm TiO ₂ + 0 ppm SiO ₂)	17.7 mm	Largest pod diameter
Average pod weight	T ₅ (50 ppm TiO ₂ + 50 ppm SiO ₂)	14.57 g	Heaviest mean pod
Pod weight per plant	T ₁₂ (100 ppm TiO ₂ + 0 ppm SiO ₂)	339.46 g	Greatest pod biomass
Pod yield	T ₁₅ (100 ppm TiO ₂ + 100 ppm SiO ₂)	12.62 t ha ⁻¹	Highest marketable yield
Minimum fiber content	T ₈ (75 ppm TiO ₂ + 0 ppm SiO ₂)	8.83%	Tender pods
Firmness	T ₁ (0 ppm TiO ₂ + 50 ppm SiO ₂)	5.59 kg cm ⁻²	Highest firmness
Net income	T ₁₅ (100 ppm TiO ₂ + 100 ppm SiO ₂)	₹164,288 ha ⁻¹	Best financial return
B:C ratio	T ₁₅ (100 ppm TiO ₂ + 100 ppm SiO ₂)	2.86	Most profitable treatment

Overall, T₁₅ was the best treatment when agronomic and economic performance were considered jointly. T₁₃ and T₅ were also highly competitive depending on whether the target trait was vegetative vigor, pod number, or pod size and weight.

4. Discussion

The superior response of okra under nano-foliar nutrition can be interpreted through the complementary roles of titanium and silicon in plant physiology. Titanium dioxide nanoparticles are widely associated with enhanced chlorophyll formation, improved light utilization, activation of enzymatic systems, and greater photosynthetic efficiency, which together support improved biomass accumulation and vegetative vigor [1, 3, 4, 7, 17, 19, 20].

This mechanistic explanation is consistent with the present findings in which TiO₂-rich combinations such as T₁₂ and T₁₃ improved chlorophyll content and plant height. The strong chlorophyll response observed in T₁₂ suggests that Nano-TiO₂ may have played a major role in sustaining photosynthetic competence during active growth [7, 17, 20].

The beneficial effect of Nano-SiO₂ is likely linked to improved cell-wall reinforcement, osmotic balance, water-use efficiency, and mitigation of abiotic stress, all of which are particularly valuable under summer field conditions [8, 9, 13, 14, 15]. Treatments containing SiO₂, especially when balanced with TiO₂ as in T₁₀, T₁₃, and T₁₅, produced stronger canopy development and superior agronomic stability, which may reflect better source-sink balance and better leaf functional duration [8, 14, 15].

An important outcome of the experiment is that the treatment best for one trait was not always the treatment best for final marketable yield. T₁₃ was superior for plant height, T₅ for pods per plant and average pod weight, T₁₂ for pod weight per plant and chlorophyll content, and T₁₅ for final yield and economics. This suggests that balanced combinational dosing creates different physiological advantages at different crop stages, and final recommendation should therefore be based on integrated agronomic performance rather than on a single response variable [5, 10, 11, 12, 16].

The significant main and interaction effects observed in the ANOVA indicate that crop response depended not only on nanoparticle dose but also on the TiO₂-SiO₂ balance. Such synergistic response is in agreement with broader literature on nanofertilizers, which emphasizes that optimized dose combinations can improve nutrient-use efficiency and crop output without proportionate increases in conventional fertilizer dependency [2, 5, 10, 11, 12, 16, 18].

The economic superiority of T₁₅ further highlights that the biological gains associated with high but balanced foliar nano application were sufficient to offset input cost under the conditions of the study. In practical terms, this is important because any recommendation for commercial cultivation must be both biologically effective and financially justified [2, 10, 11, 16].

5. Conclusion

Foliar application of Nano-TiO₂ and Nano-SiO₂ significantly improved growth, earliness, yield, quality, postharvest behavior, and economics of okra under Prayagraj conditions. The superiority of treated plots over the control was evident across vegetative, physiological, yield, and financial parameters.

Among the sixteen treatment combinations, T₁₅ (100 ppm Nano-TiO₂ + 100 ppm Nano-SiO₂) was the most effective overall and recorded the highest pod yield (12.62 t ha⁻¹), net income (₹164,288 ha⁻¹), and B:C ratio (2.86). Therefore, this treatment is recommended for maximizing okra productivity and profitability under similar agro-climatic conditions, while multi-location validation is encouraged for broader adaptation.

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