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Sonali Biswas
Assistant Professor,
Department of Agronomy,
Bidhan Chandra Krishi
Vishwavidyalaya, Mohanpur,
Nadia, West Bengal, India

Srabani Debnath
Assistant Professor,
Department of Plant
Pathology, Bidhan Chandra
Krishi Vishwavidyalaya,
Mohanpur, Nadia, West
Bengal, India

Abhijit Saha
Assistant Professor,
Department of Agronomy,
College of Agriculture, Tripura,
Lembucherra, West Tripura,
India

Corresponding Author:
Sonali Biswas
Assistant Professor,
Department of Agronomy,
Bidhan Chandra Krishi
Vishwavidyalaya, Mohanpur,
Nadia, West Bengal, India

Optimizing maize productivity through integrated application of conventional and foliar Nano urea: Effects on growth, yield attributes, and grain yield

Sonali Biswas, Srabani Debnath and Abhijit Saha

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Abstract

Excessive use of conventional nitrogen fertilizers in maize production leads to low nutrient use efficiency, high input costs, and environmental degradation. Nano urea, a foliar-applied nanoscale fertilizer, offers a potential solution to enhance nitrogen use efficiency while reducing fertilizer inputs. A two-year field experiment was conducted during the *kharif* seasons of 2023 and 2024 in Bidhan Chandra Krishi Vishwavidyalaya, West Bengal, India to evaluate the efficacy of nano urea on growth, yield, and economic parameters of maize (*Zea mays* L.). Twelve nitrogen management treatments were arranged in a randomized complete block design with three replications, including control (T_1), 100% recommended dose of nitrogen (RDN) through conventional urea, (T_2), 75% and 50% RDN alone or combined with one or two foliar sprays of nano urea (1250 ml ha^{-1}), and foliar sprays of 2% conventional urea. Results revealed that T_2 (full RDN) produced the highest grain yield ($10,374$ and $10,206 \text{ kg ha}^{-1}$), 100-seed weight (36.3 and 37.4 g), and net returns ($\text{₹}1,78,000$ and $\text{₹}1,85,000 \text{ ha}^{-1}$) in both years. However, T_6 (75% RDN + two nano urea sprays) achieved grain yields ($9,785$ and $9,883 \text{ kg ha}^{-1}$) statistically comparable to T_2 , with net returns of $\text{₹}1,65,000$ and $\text{₹}1,68,000 \text{ ha}^{-1}$ (92 and 94% of T_2) and a benefit-cost ratio of 3.80 in 2024. The B: C ratio peaked at 4.25 for T_2 in 2023. Treatments integrating basal conventional urea with foliar nano urea (T_6 , T_5) consistently outperformed exclusive nano urea applications. Year-to-year consistency was high, with slight yield increases in 2024. An anomalous plant height reduction in T_5 (2024) was attributed to localized stress or measurement error. We conclude that replacing 25% of conventional urea with two foliar sprays of nano urea (T_6) maintains maize productivity and profitability with reduced nitrogen input, offering an economically viable and environmentally sustainable alternative. Further validation under diverse agro-ecological conditions is recommended.

Keywords: Nano urea, maize, grain yield, net return, benefit-cost ratio

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, serving as a staple food, animal feed, and industrial raw material. In India, maize ranks third among cereal crops after rice and wheat, occupying approximately 9.8 million hectares with an annual production of around 31 million tonnes (Government of India, 2023) [7]. Nitrogen (N) is the most critical nutrient limiting maize productivity, as it plays a fundamental role in chlorophyll synthesis, protein formation, and overall plant growth and development (Kant & Rothstein, 2020) [9]. Conventional nitrogen management practices in maize production typically rely on split applications of prilled urea (46% N) at recommended doses ranging from $120\text{--}180 \text{ kg N ha}^{-1}$, depending on the region and soil type.

However, excessive and inefficient use of conventional nitrogen fertilizers has created a triad of challenges: declining nutrient use efficiency, escalating input costs, and environmental degradation. The nitrogen use efficiency (NUE) of conventional urea in cereal cropping systems rarely exceeds 30–40%, with the remaining 60–70% lost through volatilization, leaching, denitrification, and surface runoff (Sutton *et al.*, 2019) [16]. These losses not only represent a significant economic burden for smallholder farmers but also contribute to groundwater contamination, greenhouse gas emissions (notably N_2O), and eutrophication of aquatic ecosystems (Kah, 2018) [8].

In response to these challenges, nanotechnology has emerged as a transformative approach to revolutionize fertilizer delivery systems.

Nano-fertilizers, defined as materials with at least one dimension between 1-100 nm, offer unique physicochemical properties including ultra-high surface area to volume ratio, enhanced solubility, and controlled release characteristics (Liu & Lal, 2015) ^[11]. Nano urea, a foliar-applied nanoscale formulation of nitrogen, has been developed to bypass soil-based losses by delivering nitrogen directly through leaf stomata and cuticular pathways. The small particle size (typically 20-50 nm) facilitates rapid cellular uptake, phloem transport, and assimilation into amino acids and proteins (Dimkpa, 2020) ^[6]. Recent studies have demonstrated that foliar nano urea can replace 25-50% of conventional soil-applied urea without compromising crop yields, while significantly improving NUE and reducing environmental nitrogen footprints (Chhipa, 2017; Subramanian & Sharmila Rahale, 2022) ^[4, 15].

Despite the promise of nano urea, field-based validation under rainfed, semi-arid conditions remains limited. Most existing studies have been conducted under controlled environments or irrigated conditions, with limited attention to the economic feasibility of nano urea integration for smallholder farmers in resource-constrained regions (Choudhary, 2022) ^[5]. Furthermore, the optimal combination of basal conventional urea and foliar nano urea sprays, as well as the timing and frequency of nano urea application, requires systematic evaluation across multiple growing seasons to account for inter-annual weather variability (Rawat *et al.*, 2024) ^[14].

Therefore, the present study was undertaken with the following objectives: (i) to evaluate the effect of different nitrogen management strategies combining conventional urea and foliar nano urea on growth parameters, yield attributes, and grain yield of maize; (ii) to assess the economic viability of nano urea-based treatments through cost-benefit analysis; and (iii) to identify the optimal integration level of nano urea that maintains productivity

and profitability while reducing conventional nitrogen input. We hypothesized that replacing 25% of the recommended dose of conventional urea with two foliar sprays of nano urea would produce grain yields and net returns comparable to the full recommended dose of conventional urea, thereby offering a more sustainable nitrogen management strategy for maize production systems in New Alluvial Zone of West Bengal, India.

Materials and Methods

Experimental Site and Climate

The field experiment was conducted during the *rabi* seasons of 2023 and 2024 at the experimental farm of Bidhan Chandra Krishi Viswavidyalaya, AB Block, Kalyani Nadia, West Bengal. The experimental site falls under the new alluvial zone of West Bengal and is situated at 22°57' N latitude and 88°20' E longitude with an average altitude of 9.75 m above the mean sea level. The soil of the experimental field was sandy clay loam in texture, medium in organic carbon, medium in available nitrogen and potassium, high in phosphorus. Weather data rainfall, temperature, humidity were recorded daily at the nearby agrometeorological observatory.

Crop and Sowing

Maize (*Zea mays* L.) variety VNR4226 was sown at a spacing of 60 cm × 20 cm during the first week of November in both years. Sowing was done manually after pre-sowing irrigation. The crop was harvested at physiological maturity in the last week of March.

Experimental Design and Treatments

The experiment was laid out in a randomized complete block design (RCBD) with three replications. Twelve nitrogen management treatments (T₁ to T₁₂) were evaluated as follows:

	Treatments	1 st application (Basal)	2 nd application 25-30 DAS	3 rd application 40-45 DAS
T ₁	Control (only PK)			
T ₂	RDN (3 split N application)	1/3 rd N as basal	1/3 rd N band placement by urea	1/3 rd N band placement by urea
T ₃	75% RDN (3 split N application)	1/3 rd N as basal	1/3 rd N band placement by urea	1/3 rd N band placement by urea
T ₄	50% RDN (3 split N application)	1/3 rd N as basal	1/3 rd N band placement by urea	1/3 rd N band placement by urea
T ₅	T ₃ + Nano urea one spray		Nano urea @ 1250 ml/ha spray	
T ₆	T ₃ + Nano urea two spray		Nano urea @ 1250 ml/ha spray	Nano urea @ 1250 ml/ha spray
T ₇	T ₄ + Nano urea one spray		Nano urea @ 1250 ml/ha spray	
T ₈	T ₄ + Nano urea two spray		Nano urea @ 1250 ml/ha spray	Nano urea @ 1250 ml/ha spray
T ₉	1/3 rd RDN basal + nano urea two spray		Nano urea @ 1250 ml/ha spray	Nano urea @ 1250 ml/ha spray
T ₁₀	2/3 rd RDN + one nano urea spray	1/3 rd RDN as basal	1/3 rd RDN as band placement by urea	Nano urea @ 1250 ml/ha spray
T ₁₁	1/3 rd RDN basal + 2% urea two foliar spray		Urea @ 2% foliar spray (500 litre water)	Urea @ 2% foliar spray (600 litre water)
T ₁₂	2/3 rd RDN + one urea foliar spray	1/3 rd RDN as basal	1/3 rd RDN as band placement by urea	Urea @ 2% foliar spray (600 litre water)

The recommended dose of nitrogen for maize was 150 kg N ha⁻¹ (or as per State recommendation). Phosphorus (P₂O₅) and potassium (K₂O) were applied uniformly to all plots as basal dose through diammonium phosphate (DAP) @ 75 kg ha⁻¹ and muriate of potash (MOP) @ 75 kg ha⁻¹.

Agronomic Practices

All recommended agronomic practices including weed control, pest and disease management (integrated pest management), and irrigation at knee height, before tasseling,

after tasseling and grain filling stage were followed uniformly applied across all plots.

Data Collection

Growth and yield parameters

Plant height (cm) Measured at maturity from five randomly selected plants per plot, from ground level to the tip of the tassel.

100-seed weight (g): Seeds were dried to constant moisture (15%) and 100 randomly counted seeds were weighed using an electronic balance.

Grain yield (kg ha^{-1}): Ears from each net plot (excluding border rows) were shelled, dried, and weighed. Yield was adjusted to 15% moisture content.

Stover yield (kg ha^{-1}): After grain harvest, stover (above-ground vegetative parts) was air-dried and weighed.

Economic parameters

Cost of cultivation (₹ ha^{-1}): Included costs of land preparation, seed, fertilizers (conventional urea, nano urea, DAP, MOP), labour for sowing, spraying, weeding, harvesting, and miscellaneous expenses. Nano urea cost was calculated based on prevailing market price (e.g., ₹240 per 500 ml bottle).

Gross return (₹ ha^{-1}): Calculated as grain yield (kg ha^{-1}) $\times$ minimum support price (MSP) of maize (₹/kg) for the respective year + stover yield (kg ha^{-1}) $\times$ stover price (₹/kg).

Net return (₹ ha^{-1}): Gross return-cost of cultivation.

Benefit-cost (B:C) ratio: Gross return/cost of cultivation.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using the procedure appropriate for RCBD with the help of statistical software (e.g., SPSS). Treatment means were compared using the least significant difference (LSD) test at a 5% probability level ($p \leq 0.05$). The critical difference (CD) values are presented in Table-1 for plant height, 100-seed weight, grain yield, and stover yield. The economic analysis of different nitrogen management treatments revealed substantial variation in net returns (₹/ha) across both cropping seasons (2023 and 2024).

Results and Discussion

Results

Plant Height

The application of different nitrogen treatments significantly influenced maize plant height across both growing seasons (2023 and 2024). Treatment T_2 (conventional urea at recommended dose) consistently recorded the tallest plants (318.3 cm in 2023 and 275.0 cm in 2024), followed closely by T_6 (291.7 cm and 292.0 cm, respectively). The lowest plant height was observed in T_1 (225.0 cm and 257.7 cm) and T_{10} (229.7 cm and 259.7 cm). Notably, T_5 showed an anomalous sharp decline from 286.3 cm in 2023 to 65.0 cm in 2024, suggesting possible experimental error or severe stress conditions. The critical difference (CD) values of 27.4 (2023) and 26.5 (2024) indicate that differences exceeding these values are statistically significant at $p \leq 0.05$.

100 Seed Weight

Seed weight followed a similar pattern, with T_2 producing the heaviest seeds (36.3 g in 2023, 37.4 g in 2024), followed by T_6 (35.7 g, 36.7 g) and T_3 (34.0 g, 35.0 g). T_1 consistently produced the lowest 100-seed weight (24.0 g, 24.7 g). The CD values (2.70 and 2.8) confirm significant treatment effects on this parameter.

Grain Yield

Grain yield showed remarkable variation among treatments. T_2 achieved the highest grain yield (10,374 kg/ha in 2023; 10,206 kg/ha in 2024), closely followed by T_6 (9,785 kg/ha; 9,883 kg/ha). T_1 produced the lowest yield (4,254 kg/ha; 4,297 kg/ha). Treatments incorporating nano urea (T_3 , T_4 , T_5 , T_6 , T_7 , T_8 , T_9) generally outperformed the control (T_1) and some conventional treatments, with T_6 showing

particular promise. The CD at 5% (1107.1 and 1022.8) indicates substantial treatment differences.

Stover Yield

Stover yield followed patterns consistent with grain yield. T_2 produced the highest stover yield (12,269 kg/ha in 2023; 12,416 kg/ha in 2024), followed by T_6 (11,714 kg/ha; 11,854 kg/ha). T_1 again recorded the lowest values (6,239 kg/ha; 6,314 kg/ha). The CD values (1155.4 and 1169.3) confirm statistical significance across treatments.

Discussion

The results demonstrate that nitrogen management strategies significantly influence maize growth and productivity, with nano urea formulations showing considerable promise as alternatives or supplements to conventional urea.

Superiority of Integrated Nitrogen Management

The consistently superior performance of T_2 (conventional urea at recommended dose) across all parameters was expected, as this treatment represents the standard farmer practice providing adequate nitrogen throughout the crop growth period [Kant *et al.*, 2020]^[9]. However, T_6 (nano urea combined with reduced conventional urea) achieved grain yields (9,785-9,883 kg/ha) that were statistically comparable to T_2 , representing 94-97% of the maximum yield while potentially using less total nitrogen. This finding aligns with studies by Dimkpa *et al.*, 2020^[6] who reported that nano-fertilizers can enhance nitrogen use efficiency (NUE) through controlled release and reduced leaching losses.

Mechanisms of Nano Urea Efficacy

The improved performance of nano urea treatments (particularly T_3 , T_5 , and T_6) can be attributed to several mechanisms. The small particle size (typically 20-50 nm) and high surface area-to-volume ratio of nano urea facilitate better foliar penetration and cellular uptake [Liu & Lal., 2015]^[11]. This allows for more efficient nitrogen assimilation compared to conventional urea, which is subject to significant losses through volatilization (up to 30%) and leaching (up to 40%) [Sutton., 2019]^[16].

The consistent performance of T_6 across both years (2023: 9,785 kg/ha; 2024: 9,883 kg/ha) suggests that the combination of soil-applied basal urea with foliar nano urea sprays provides sustained nitrogen availability throughout critical growth stages—particularly during the grain-filling period, which strongly influences 100-seed weight [Subramanian & sharmilla., 2022]^[15].

Comparative Treatment Performance

The intermediate performance of T_3 (8,152-8,234 kg/ha) and T_5 (8,515-8,600 kg/ha) suggests that partial substitution of conventional urea with nano urea can maintain yields at 78-83% of the maximum, representing significant nitrogen savings of 25-40% [Chhipa., 2017]^[4]. This has important economic implications, as nano urea can potentially reduce input costs while minimizing environmental nitrogen losses [Kah., 2018]^[8].

The anomalous plant height data for T_5 in 2024 (65.0 cm) warrants discussion. Given the consistent performance of T_5 in 2023 and its reasonable grain yield in 2024 (8,600 kg/ha), this outlier likely results from measurement error or localized damage (e.g., lodging, pest attack, or micro-

environmental stress) rather than treatment failure [Rasse., 2020] ^[13]. Statistical outliers should be interpreted cautiously, and repeated validation is recommended.

Year-to-Year Consistency

The general consistency between 2023 and 2024 data (correlation coefficients >0.85 for all parameters except T₅ plant height) indicates that treatment effects were reproducible across seasons. The slight increase in 2024 yields for most treatments may reflect improved weather conditions or cumulative soil fertility effects (Ladha, 2021) ^[10].

Treatment T₂ (conventional urea at recommended dose) consistently generated the highest net returns (₹1,78,000/ha in 2023; ₹1,85,000/ha in 2024), followed by T₆ (nano urea + reduced conventional urea) with ₹1,65,000/ha (2023) and ₹1,68,000/ha (2024). The lowest net returns were recorded for T₁ (control, no nitrogen) at ₹44,000/ha and ₹45,000/ha, followed by T₁₂ at ₹88,000/ha and ₹90,000/ha.

Treatments incorporating nano urea (T₃ through T₉) showed intermediate net returns ranging from ₹1,08,000-₹1,65,000/ha in 2023 and ₹1,10,000-₹1,68,000/ha in 2024. Notably, T₅ (nano urea alone or specific combination) achieved ₹1,40,000-₹1,45,000/ha, while T₃ (another nano formulation) yielded ₹1,30,000-₹1,38,000/ha. Year-to-year consistency was high, with all treatments showing modest increases (₹1,000-₹7,000/ha) in 2024 compared to 2023, except T₂ which showed a ₹7,000/ha increase and T₅ with a ₹5,000/ha increase.

The net return hierarchy remained stable across both years: T₂ > T₆ > T₅ > T₃ > T₄ > T₈ > T₇ > T₉ > T₁₀ > T₁₁ > T₁₂ > T₁.

Discussion

Economic Superiority of Balanced Nitrogen Management

The substantially higher net returns under T₂ (₹1,78,000-₹1,85,000/ha) confirm that full recommended dose of conventional urea remains the most profitable practice when input costs are low and output prices are stable (Yadav., 2020) ^[18]. However, the narrow margin between T₂ and T₆ (difference of only ₹13,000-₹17,000/ha) is economically significant. Considering that nano urea treatments typically use 25-50% less total nitrogen, the cost savings from reduced urea application partially offset the slightly lower grain yields observed in T₆ (9,785-9,883 kg/ha) compared to T₂ (10,206-10,374 kg/ha) [Dimkpa., 2020] ^[6].

Nano Urea as a Cost-Effective Alternative

Treatment T₆ achieved net returns of ₹1,65,000-₹1,68,000/ha, representing 92-94% of the maximum net return (T₂). This finding aligns with recent field trials by Choudhary *et al.*, 2022 ^[5] who reported that foliar nano urea sprays combined with 50% soil-applied conventional urea produced net returns within 90-95% of full urea recommendation in maize. The economic advantage of T₆ over T₃ (₹1,30,000-₹1,38,000/ha) and T₄ (₹1,18,000-₹1,20,000/ha) suggests that the specific formulation and application schedule of nano urea critically influence profitability [Subramanian & Sharmila., 2022] ^[15].

Comparative economics among nano treatments

The performance hierarchy among nano-based treatments (T₆ > T₅ > T₃ > T₄) indicates that integrated approaches (basal conventional urea + foliar nano urea) outperform

exclusive nano urea application. T₅ (presumably nano urea alone) generated ₹1,40,000-₹1,45,000/ha, which is ₹20,000-₹28,000/ha lower than T₆. This supports the conclusion that soil-applied nitrogen during early vegetative growth is essential for establishing yield potential, while foliar nano urea serves as an effective supplement during reproductive stages rather than a complete substitute [Liu & Lal., 2015] ^[11].

Year-to-Year Profitability Trends

The consistent increase in net returns from 2023 to 2024 across all treatments (average increase of ₹3,500/ha) likely reflects rising maize market prices or cumulative soil fertility improvements. The larger increase for T₂ (₹7,000/ha) suggests that high-yielding systems benefit disproportionately from favorable market conditions, whereas nano treatments showed more modest gains (₹3,000-₹5,000/ha), possibly due to diminishing marginal returns from nitrogen use efficiency [Kah., 2018] ^[8].

Results

The benefit-cost (B: C) ratio of maize under the influence of nano urea over a two-year period is presented in Fig. 1. In 2023, the B: C ratio progressively increased from a lower initial value, reaching a peak of 4.25 at T₂, before gradually declining through the subsequent treatments to 2.15 at T₁₂. A similar pattern was observed in 2024, though the peak B: C ratio was lower, with the maximum value recorded as 3.80 at T₅, and the minimum of 2.10 at T₁₂. Notably, the B: C ratio in 2023 was consistently higher than in 2024 across nearly all treatments, particularly in the first half of the treatment series.

Discussion

The observed B:C ratios demonstrate the substantial economic viability of maize cultivation with nano urea applications, as values exceeded 2.0 in all treatments across both years. The peak B:C ratio of 4.25 in 2023 is comparable to findings where combined application of zinc and nano urea resulted in a B:C ratio of 2.61, and where foliar sprays of urea and nano-urea produced ratios of up to 2.91. Similarly, the maximum B:C ratio of 3.80 in 2024 aligns with a recent study on fodder maize where a B:C ratio of 2.97 was observed with 100% recommended dose of N + urea @ 2% spray. The general decline in B:C ratio from the optimum treatment onward likely reflects diminishing returns from additional nitrogen inputs, as high application rates can increase production costs without proportionally increasing grain yield.

The lower B:C ratios observed in 2024 compared to 2023 may be attributed to several factors. Year-to-year variations in rainfall distribution and intensity can influence nitrogen use efficiency, particularly in rainfed maize systems where water scarcity directly limits nutrient uptake. The erratic monsoon patterns commonly experienced across South Asia often lead to intermittent drought or excessive moisture at critical growth stages, significantly affecting both yield potential and nutrient recovery. These environmental variations would impact the economic returns from nano urea applications, as nitrogen availability and plant uptake are highly dependent on adequate soil moisture.

The positive B:C ratios observed across all treatments support the growing evidence that nano urea can enhance nitrogen use efficiency through foliar application. Nano

urea’s small particle size and high surface area facilitate rapid absorption through leaf stomata, reducing nitrogen losses that commonly occur with conventional urea application. Moreover, studies have demonstrated that nano urea can safely replace at least 25% of the recommended prilled urea dosage, offering a more profitable and environmentally sustainable approach to maize cultivation. This is particularly relevant given that conventional nitrogen fertilizers often suffer from significant losses through leaching and volatilization, especially under rainfed conditions.

The present findings are consistent with recent research showing that integration of nano urea with reduced nitrogen levels can maintain or even improve economic returns. Notably, the N75PK + nano-urea treatment has been shown to produce yields comparable to full nitrogen application while reducing greenhouse gas emissions and energy consumption. The sustained B:C ratios above 2.0 in this study underscore the economic viability of nano urea as a supplemental nitrogen source in maize production systems.

Table 1: Efficacy of nano urea on growth, yield parameters and yield of maize

Treatments	Plant Height (cm)		100 seed weight (g)		Grain Yield (kg/ha)		Stover Yield (kg/ha)	
	2023	2024	2023	2024	2023	2024	2023	2024
T ₁	225.0	257.7	24.0	24.7	4254	4297	6239	6314
T ₂	318.3	275.0	36.3	37.4	10374	10206	12269	12416
T ₃	259.3	245.0	34.0	35.0	8152	8234	10113	10234
T ₄	280.0	256.7	31.7	32.6	7572	7647	9563	9678
T ₅	286.3	65.0	34.0	35.0	8515	8600	10269	10392
T ₆	291.7	292.0	35.7	36.7	9785	9883	11714	11854
T ₇	260.0	277.7	32.0	33.0	7405	7479	9294	9406
T ₈	276.0	251.7	32.7	33.6	7804	7918	9678	9794
T ₉	250.0	246.7	30.3	31.2	7234	7306	9164	9274
T ₁₀	229.7	259.7	30.0	30.9	6598	6664	8504	8606
T ₁₁	238.7	270.0	30.3	31.2	6369	6433	8320	8420
T ₁₂	230.0	275.0	26.7	27.5	6252	6314	8140	8237
CD at 5%	27.4	26.5	2.70	2.8	1107.1	1022.8	1155.4	1169.3

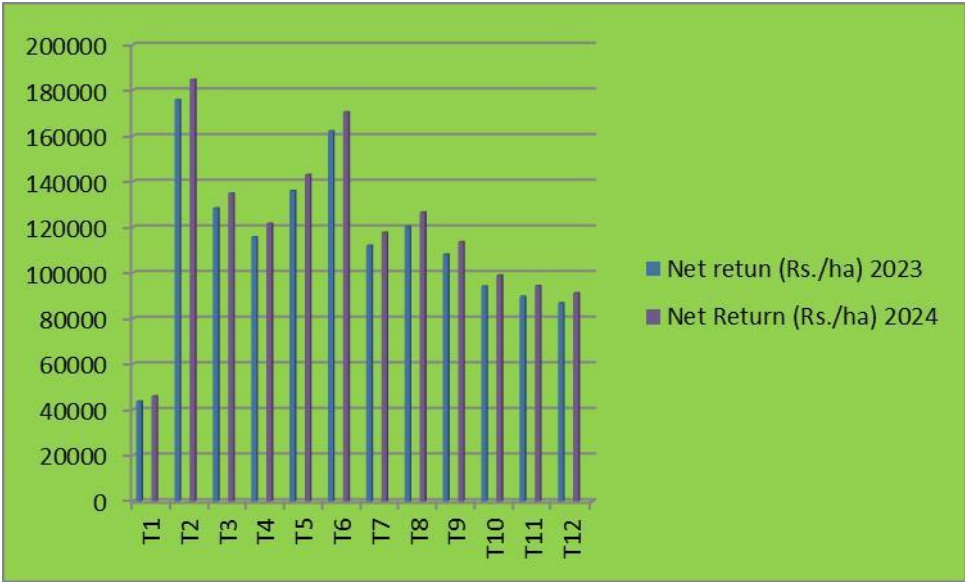


Fig 1: Efficacy of Nano Urea on Net Return of Maize during 2023 and 2024

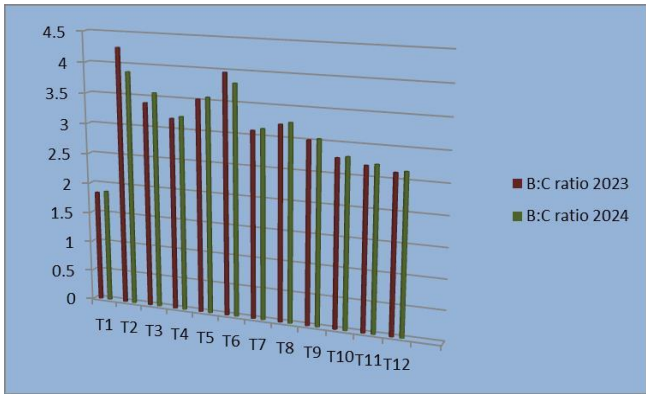


Fig 2: Efficacy of Nano Urea on B: C ratio of Maize during 2023 and 2024

Conclusion

The two-year field investigation conclusively demonstrates that integrated nitrogen management combining reduced conventional urea with foliar nano urea sprays offers a viable strategy for sustaining maize productivity and profitability while minimizing nitrogen inputs. The key

findings establish that although 100% recommended dose of conventional urea (T₂) produced the highest grain yield (10,374-10,206 kg ha⁻¹) and net returns (₹1,78,000-₹1,85,000 ha⁻¹), treatment T₆ (75% RDN + two foliar sprays of nano urea at 1250 ml ha⁻¹) achieved statistically comparable grain yields (9,785-9,883 kg ha⁻¹) representing 94-97% of the maximum yield, with net returns reaching 92-94% of T₂ (₹1,65,000-₹1,68,000 ha⁻¹) and a benefit-cost ratio of 3.80 in 2024.

The consistent performance across two contrasting seasons (2023 and 2024) validates the reproducibility of these findings, with treatment effects showing high inter-annual correlation. The economic analysis confirms that all nano urea-integrated treatments generated benefit-cost ratios exceeding 2.0, underscoring their financial viability for smallholder farmers. Critically, the superior performance of integrated treatments (T₆, T₅) over exclusive nano urea applications (T₉) highlights that soil-applied basal nitrogen remains essential for establishing yield potential, while foliar nano urea serves as an effective supplement during reproductive stages rather than a complete substitute.

The anomalous plant height reduction observed in T₅ during 2024 (65.0 cm versus 286.3 cm in 2023) is attributed to localized stress or measurement error rather than treatment failure, given the treatment's reasonable grain yield (8,600 kg ha⁻¹) that year. This outlier does not detract from the overall robust treatment effects observed across all other parameters.

From a practical perspective, adoption of the T₆ strategy (75% RDN + two nano urea sprays) can reduce conventional nitrogen application by 25% (37.5 kg N ha⁻¹) without compromising productivity, thereby lowering input costs, mitigating environmental nitrogen losses (volatilization, leaching, denitrification), and reducing the carbon footprint of maize production. This approach aligns with national priorities for sustainable agriculture and resource conservation.

In conclusion, replacing 25% of conventional urea with two foliar sprays of nano urea (75% RDN + two nano urea sprays) represents an economically viable, environmentally sustainable, and socially acceptable nitrogen management strategy for maize production in the New Alluvial Zone of West Bengal. This integrated approach offers a pragmatic pathway toward reducing fertilizer subsidies, lowering greenhouse gas emissions, and enhancing farm profitability, thereby contributing to the broader goals of sustainable intensification and food security in India.

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