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Role of integrated nano macro and micro nutrients with commercial fertilizers on growth, yield and economics of turmeric (*Curcuma longa* L.) cv. suguna

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Abstract

Now a days application nano-fertilizers in horticulture become an effective nutrient management strategy for improving crop growth, yield and quality by enhancing nutrient use efficiency, reducing nutrient losses and lowering production costs through precision nutrient delivery. Considering the facts a two-year field investigation was conducted during 2022-23 and 2023-24 at the Horticultural Research Station, Mondouri, BCKV, West Bengal, to evaluate the effect of integrated nano-formulated macro (N, P and K) and micronutrients (Zn, Mn and Cu) with commercial fertilizers on the growth, yield and economics of turmeric cv. Suguna. The experiment was laid out in a Randomized Block Design with eight treatments and three replications. Among the treatments, application of 40% N + 75% P as basal followed by 0.4% nano P at 45 DAP and 0.4% nano N+K+Zn+Mn+Cu at 45 and 90 DAP (T₈) recorded the highest plant height (92.65 cm and 160.05 cm), tillers per plant (1.50 and 2.61), leaf number (9.16 and 17.06) at 90 and 150 DAP, clump weight (442.40 g), weight (303.54 g) and number (19.67) of primary finger and secondary finger weight (106.73 g). The treatment also produced the maximum plot yield (14.30 kg 3 m⁻²) and projected yield (35.76 t ha⁻¹). Economic analysis revealed that T₈ recorded the highest gross return (₹6, 43,680 ha⁻¹), net return (₹4, 35,758 ha⁻¹) and B:C ratio (2.10). The study reveals that integrating nano-formulated macro and micronutrients with commercial fertilizers substantially enhanced growth, yield and profitability of turmeric while reducing dependence on conventional fertilizers. Therefore, integrated nano nutrient management represents a sustainable and economically viable strategy for improving fertilizer use efficiency and turmeric production.

Keywords: Turmeric, nano macronutrients, nano micronutrients, yield, benefit-cost ratio

Introduction

Curcuma longa L. (turmeric) is one of the most important commercial spice crop belongs to the family Zingiberaceae. It is widely cultivated throughout tropical and subtropical regions of the world. The crop is native to the Indian subcontinent and widely called Haldi due to its rich yellow colour. Beside use as spice turmeric also hold a unique position as medicinal herb, natural food colourant and industrial raw material owing to the presence of bioactive compounds, particularly curcuminoids, volatile oils (2.5-7.5%) and oleoresins (7-15%). Among these, curcumin (1.8-5.4%) impart antioxidant, anti-inflammatory, antimicrobial and anticancer properties (Marotta, 2003) [14]. India is the largest producer, consumer and exporter of turmeric, contributing nearly 75-80% of the world's production and dominating the international spice market (Sil *et al.* 2026) [20]. Despite this leading position, sustaining productivity while maintaining superior rhizome quality under intensive cultivation remains a major challenge.

Turmeric is a long-duration (7-9 months) exhaustive crop with high nutrient requirements because of its luxuriant vegetative growth and uneven nutrient demand throughout its growth period (Sil and Hore, 2026) [19]. Adequate and balanced nutrition plays a pivotal role in maximizing growth, rhizome yield, quality attributes and economic returns (Bairagi, 2022) [3]. But the continuous use of recommended doses of conventional fertilizers results in low nutrient use efficiency due to volatilization, leaching loss, denitrification, fixation and runoff. It has been reported that only about 30-60% of applied nitrogen, 15-25% of phosphorus and 40-60% of potassium are effectively utilized by crops, while the remaining nutrients contribute to environmental pollution, soil degradation and increased production costs (Dutta and Bera, 2021) [4]. These challenges necessitate the development of innovative nutrient

management strategies that enhance nutrient use efficiency while ensuring sustainable crop production.

Nanotechnology has emerged as a promising frontier in modern agriculture, offering innovative solutions to improve nutrient delivery and crop productivity. Nano-fertilizers are engineered nutrient formulations with particle sizes generally ranging from 1 to 100 nm, possessing unique physicochemical properties such as high surface area, greater reactivity, enhanced solubility and controlled nutrient release (Tang *et al.*, 2024) [21]. These characteristics facilitate efficient nutrient absorption, translocation and utilization within plants, thereby reducing nutrient losses and increasing fertilizer use efficiency. Foliar application of nano-fertilizers has attracted considerable attention because nutrients are rapidly absorbed through leaf surfaces, bypassing several soil-related constraints associated with conventional fertilization (Yadav *et al.*, 2023) [22]. Nano-fertilizers have the potential to reduce fertilizer requirements, minimize environmental contamination and improve crop productivity at a low concentration. Integration of nano-fertilizers with commercial fertilizers has recently gained considerable attention as a balanced nutrient management approach rather than complete replacement of conventional fertilizers. Such integrated nutrient management combines the advantages of soil-applied fertilizers for meeting basal crop nutrient requirements with foliar nano-fertilizers that efficiently supplement nutrients during critical growth stages.

Although there are various studies has been done on the effect of nano fertilizers on various horticultural crops but the information regarding integrated application of nano macro and micro nutrients in turmeric remains limited. Considering these knowledge gaps, the present investigation was undertaken to evaluate the effect of integrated nano-formulated macro (N, P and K) and micronutrients (Zn, Cu and Mn) in combination with commercial fertilizers. The study aimed to assess their influence on vegetative growth, rhizome development, yield attributes, productivity and economic returns, and to identify an efficient and sustainable nutrient management strategy for improving fertilizer use efficiency and enhancing the profitability of turmeric cultivation.

Materials and Methods

Details of experimental site: The two-year (2022-23 and 2023-24) field experiment was conducted at Horticultural Research Station, Mondouri, Bidhan Chandra Krishi Viswavidyalaya, West Bengal. The experimental field was located at 23°05' N latitude and 89°00' E longitude at an altitude of 9.75 m above mean sea level. The site experienced an average temperature of 25.96 °C, rainfall of 33.44 mm and relative humidity of 83.60% for the period of June, 2022 to January 2024. The soil of the experimental site falls under the gangetic new alluvial plains of West Bengal and possesses a sandy clay loam texture with a proper moisture holding capacity (Table 1).

Experimental design: The experiment was laid out in Randomized Block Design with 8 treatments and 3 replications, altogether 24 plots (Table 2). Raised beds of 3 m² with a height of 15 cm were prepared for planting.

Planting: The turmeric variety Suguna was planted during middle of June in both the years. Disease free healthy seed rhizomes (25-30 g) containing at least 2-3 viable buds were used for planting at a depth of 5 cm with a spacing of 30 cm

× 25 cm in the experimental plots which accommodate 40 plants per bed.

Seed treatment: Seed rhizomes were treated with blitox @ 4 g L⁻¹ for 30 minutes and dried in shade to avoid any fungal infection of the crop just before planting.

Manures and fertilizers: During land preparations 25 t ha⁻¹ well decomposed Farmyard Manure (FYM) was uniformly incorporated into the soil and the field was subsequently levelled up. The plots were fertilised with the recommended dose of N: P₂O₅:K₂O @ 150:60:150 kg ha⁻¹ (Medda and Hore, 2003) supplied through urea (46% N), single superphosphate (16% P₂O₅) and muriate of potash (60% K₂O), respectively as per the treatments. The full dose of phosphorus and 40% of the nitrogen were applied as a basal dose during planting, while the remaining nitrogen and full dose of potassium were applied in two equal splits at 45 and 90 days after planting.

Application of nanofertilizer and spraying: Nano macro (N, P and K) and nano micronutrients (Zn, Mn and Cu) were applied at two critical growth stages *i.e.* 45 and 90 DAP through foliar spray using a hand-operated knapsack sprayer. Foliar spray was done on the upper surface of leaf until near runoff condition during morning hours.

Nano-formulation solution preparation: The foliar spray solutions were prepared freshly by dissolving the required quantity of nano-fertilizers in water according to the treatment s. To improve the retention of the spray droplets on the leaf surface and facilitate efficient nutrient uptake, two to three drops of a surfactant (Balanstick) were incorporated per litre of the prepared solution. Liquid nano-fertilizers, namely nano nitrogen and nano phosphorus, were diluted @ 1 mL L⁻¹ of water to obtain a 0.1% solution, whereas powdered nano-fertilizers (nano potassium, zinc, manganese and copper) were dissolved at 1 g L⁻¹ of water to achieve the same concentration. For preparing a 0.4% spray solution, the appropriate quantity of each nano-fertilizer was initially dissolved in a small volume of distilled water to ensure complete dissolution, and the volume was subsequently adjusted to one litre with distilled water before application.

Irrigation and intercultural operation: The plots were irrigated immediately after planting and rest of other irrigations were given based on soil moisture availability. Mulching was applied with paddy straw @ 10 t ha⁻¹ just after planting and additional mulching was provided at 45 and 90 DAP using paddy straw at 5 t ha⁻¹, and earthing up was carried out prior to the second and third mulching operations.

Observations and statistical analysis: Growth parameters like plant height (cm), tiller and leaf number, leaf dimension (length and breadth) were recorded from five randomly selected plants of each plot at 90 and 150 DAP. The various clump characteristics (weight, length and breadth), primary and secondary finger attributes (number, weight, length and breadth) were recorded from five rhizomes of each plot. Plot yield was measured after harvesting of all the rhizomes from each plot. Projected yield was calculated based on the plot yield considering 75% area of the plot covered by crop and rest 25% for pathways, irrigation channel etc. Formula for calculating projected yield is - plot yield (kg 3m⁻²) × 2500 (Anonymous, 1995) [1].

The economic evaluation of the different nutrient management treatments was performed by estimating the cost of cultivation, gross return, net return and benefit-cost

(B:C) ratio based on the expenses incurred for various production inputs and the average market price of turmeric prevailing during the experimental period. The cost of cultivation included expenditures on farmyard manure (FYM) (₹2,000 t⁻¹), urea (46% N) (₹5.92 kg⁻¹), single super phosphate (SSP, 16% P₂O₅) (₹10.00 kg⁻¹), muriate of potash (MOP, 60% K₂O) (₹34.00 kg⁻¹), nano nitrogen (₹258.00 L⁻¹), nano phosphorus (₹587.40 L⁻¹), nano potash (₹719.60 kg⁻¹), nano combi i.e. Zn+ Mn + Cu (₹ 291.00 50 g⁻¹) seed rhizomes (₹30.00 kg⁻¹), labour charges (₹363.00 man day⁻¹), tractor hire (₹1,000.00 h⁻¹) and irrigation charges (₹50.00 h⁻¹). The average selling price of fresh turmeric rhizomes was considered as ₹18.00 kg⁻¹ for calculating the economic returns. Gross Return (GR) was computed by multiplying the projected rhizome yield by the prevailing market price, whereas Net Return (NR) was obtained by deducting the total cost of cultivation from the corresponding gross return. The benefit-cost (B:C) ratio was determined using the following formula:-

$$\text{Benefit cost ratio} = \frac{\text{Net return}}{\text{Cost of production}}$$

All experimental observations were subjected to statistical analysis using the Analysis of Variance (ANOVA) technique as outlined by Gomez and Gomez (1984) [7]. The significance of treatment effects was assessed through Fisher's F-test at the 5% probability level. Whenever the treatment effects were found to be significant, the Critical Difference (CD) at $p=0.05$ was calculated following the procedure described in the statistical tables of Fisher and Yates (1953) [5] for comparison of treatment means.

Results

Growth parameters

The data presented in Table 3 clearly indicates a significant variation on plant height at 90 and 150 DAP. The maximum plant height (92.65 cm and 160.05 cm) was recorded under the treatment T₈ where the minimum plant height (71.71 cm and 133.77 cm) was recorded under T₁. The results presented in Table 3 revealed that nano-formulated macro and micronutrients have significant effect on the number of tillers per plant at 90 and 150 DAP. The highest number of tillers (1.50) was recorded under T₈, followed by T₆ (1.44) at 90 DAP. Where at 150 DAP T₈ recorded the maximum number of tillers per plant (2.61), followed by the plants grown under T₄ (2.46). In contrast the lowest tiller production (1.03 and 1.74) was observed under T₁ at 90 and 150 DAP.

Data presented in Table 4 revealed that leaf length and breadth showed a significant variations among the treatments. At 90 and 150 DAP T₈ recorded maximum leaf length (35.56 cm and 73.04 cm) which are statistically *at par* with T₆ (35.31 cm and 72.15 cm), while T₁ recorded the lowest length of leaves (31.33 cm and 64.37 cm). On the other hand maximum leaf breadth at 90 DAP (10.94 cm) was recorded under T₈ which is statistically *at par* with T₆ (10.81 cm) where T₄ recorded the highest leaf breadth (15.77 cm) at 150 DAP followed by T₈ (15.72 cm). The minimum leaf breadth at 90 and 150 DAP (9.83 cm and 14.88 cm) were observed under T₁. The number of leaves showed significant variations among the treatments (Table.5). Maximum leaf number (9.16 and 17.06) was

recorded under T₈ at 90 and 150 days after planting which are statistically *at par* with T₄ (9.07 and 16.84), as compared to the lowest number of leaves (7.20 and 14.01) was observed under T₁.

Yield parameters

The results presented in Table 5 clearly demonstrate that the clump characterises varied significantly among the treatments due to application of nano macro and micro nutrients integrated with commercial fertilizers. Data reveals that maximum clump weight (442.40 g), length (24.29 cm) and breadth (16.97 cm) were recorded under T₈. Plants grown under T₁ recorded minimum value underweight (276.04 g), length (21.45 cm) and breadth (13.60 cm) of clump (Fig.1).

The length of primary finger depicted in Table 6 showed significant differences among treatments. Results revealed that T₈ recorded the maximum primary finger weight (303.54 g), number (19.67), length (8.79 cm) and breadth (2.23 cm). Whereas the treatment T₁ recorded the lowest weight (175.41 g) and number (12.93) of primary fingers. But the lowest length of primary fingers (7.84 cm) was observed in T₂, while T₃ recorded the minimum breadth of primary fingers (1.63 cm).

The secondary fingers characteristics differed significantly among the treatments (Table 7). The maximum number (9.58), weight (106.73 g) and length (4.50 cm) of secondary fingers, were recorded under T₈, while widest breadth of secondary fingers (2.08 cm) was recorded under T₆. Treatment T₂ recorded the minimum number of secondary fingers (8.47). Lowest weight of secondary finger (68.49 g) was recorded under T₃. While the lowest length of secondary fingers (3.34 cm) was observed in T₅. The minimum breadth (1.44 cm) was recorded under the treatment T₁.

It was evident from the data presented in Table 8 that application of nano macro and micro nutrients integrated with commercial fertilizers had significant effect on both the plot and projected yield in both the year and pooled analysis. Plants grown under T₈ recorded the highest plot (14.30 kg 3m⁻²) and projected (35.76 t ha⁻¹) yield, while T₁ recorded the lowest plot (10.57 kg 3m⁻²) and projected (26.42 t ha⁻¹) yield.

The results obtained from Table 9 and depicted in Fig.2 indicated the marked variations among the different nano formulation of macro and micro-nutrients integrated with commercial fertilizers with respect to cost of production, gross return, net return and B:C ratio during both the years and in mean data. As per mean data, the maximum cost of production of Rs. 214886/- was recorded under T₁ followed by T₅ (Rs. 214661/-) as compared to T₈ (Rs. 207922/-). The maximum gross return (Rs. 643680/-) was observed in T₈, followed by T₄ (Rs. 616230/-) as compared to lowest gross return in T₁ (Rs. 475560/-). In case of net return, the maximum value of Rs. 435758/- was recorded in T₈, followed by T₄ (Rs. 408083/-) while the lowest value was associated with T₁ (Rs. 260674/-). The highest B: C ratio was noticed in T₈ (2.10) followed by T₄ (1.96). The lowest value was observed in T₁ (1.21).

Table 1: Physio-chemical attributes of the experimental soil before planting

Soil pH	Organic carbon (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
6.62	0.67	229.71	18.53	210.65

Table 2: Details of the treatment

Sl. No.	Treatment combination
T ₁	40% N+100% P (B)→ 30% N+50% K (45 and 90 DAP) + 0.4% nano Zn+Mn+Cu
T ₂	40% N+100% P (B)→ 0.4% Nano N+50% K (45 DAP and 90 DAP) + 0.4% nano Zn+Mn+Cu
T ₃	40% N+100% P (B)→ 30% N+0.4% Nano K (45 DAP and 90 DAP) + 0.4% nano Zn+Mn+Cu
T ₄	40% N+100% P (B)→ 0.4% Nano N and K (45 DAP and 90 DAP) + 0.4% nano Zn+Mn+Cu
T ₅	40% N+75% P (B)→ 30% N+0.4% Nano P+50% K (45 DAP)→ 30% N+50% K (90 DAP) + 0.4% nano Zn+Mn+Cu
T ₆	40% N+75% P (B)→ 0.4% Nano N and P+ 50% K (45 DAP)→ 0.4% Nano N+50% K (90 DAP) + 0.4% nano Zn+Mn+Cu
T ₇	40% N+75% P (B)→ 30% N + 0.4% Nano P and K (45 DAP)→ 30% N +0.4% Nano K (90DAP) + 0.4% nano Zn+Mn+Cu
T ₈	40% N+75% P (B)→ 0.4%Nano N, P and K (45 DAP) → 0.4% Nano N and K (90DAP) + 0.4% nano Zn+Mn+Cu

B: Basal, DAP: Days after planting, nano Zn+Mn+Cu was applied at 45 and 90 DAP

Table 3: Effect of nano macro and micro nutrients on plant height and tiller number

Treatments	Plant height (cm)						Tiller number per plant					
	90 DAP			150 DAP			90 DAP			150 DAP		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T ₁	69.58	73.83	71.71	134.23	133.30	133.77	1.05	1.01	1.03	1.67	1.81	1.74
T ₂	76.27	84.24	80.25	145.74	148.83	147.29	1.25	1.47	1.36	1.95	2.34	2.15
T ₃	80.75	75.51	78.13	141.68	144.36	143.02	1.13	1.24	1.19	1.82	2.03	1.93
T ₄	86.38	86.92	86.65	156.05	158.11	157.08	1.28	1.54	1.41	2.31	2.61	2.46
T ₅	78.22	84.58	81.40	139.22	147.46	143.34	1.21	1.34	1.28	1.81	2.15	1.98
T ₆	86.09	94.69	90.39	148.85	156.98	152.92	1.39	1.49	1.44	2.28	2.57	2.43
T ₇	79.25	88.02	83.64	153.43	157.08	155.26	1.32	1.40	1.36	2.05	2.43	2.24
T ₈	84.75	100.56	92.65	155.87	164.22	160.05	1.48	1.51	1.50	2.46	2.75	2.61
S.Em. (±)	1.012	1.137	1.090	1.964	1.994	1.981	0.017	0.023	0.018	0.027	0.038	0.031
C.D. (P=0.05)	3.099	3.483	3.339	6.014	6.108	6.066	0.052	0.069	0.054	0.083	0.117	0.094

Table 4: Effect of nano macro and micro nutrients on leaf diameter

Treatments	Leaf length (cm)						Leaf breadth (cm)					
	90 DAP			150 DAP			90 DAP			150 DAP		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T ₁	30.75	31.92	31.33	62.81	65.92	64.37	9.28	10.38	9.83	14.49	15.27	14.88
T ₂	32.56	33.33	32.95	66.12	70.32	68.22	9.87	10.33	10.10	14.92	15.34	15.13
T ₃	31.02	33.37	32.19	71.06	69.88	70.47	10.21	10.40	10.31	15.22	15.17	15.20
T ₄	34.69	35.53	35.11	67.64	75.38	71.51	10.81	10.73	10.77	15.83	15.71	15.77
T ₅	33.81	34.16	33.98	66.78	69.94	68.36	9.85	11.35	10.60	14.75	15.39	15.07
T ₆	34.57	36.05	35.31	69.03	75.26	72.15	10.70	10.91	10.81	14.99	15.56	15.28
T ₇	32.46	35.71	34.09	69.98	70.05	70.02	10.28	11.03	10.66	15.30	15.41	15.36
T ₈	34.83	36.28	35.56	73.81	72.27	73.04	10.60	11.29	10.94	15.56	15.87	15.72
S.Em. (±)	0.547	0.455	0.479	1.158	1.210	1.172	0.132	0.179	0.152	0.201	0.208	0.260
C.D. (P=0.05)	1.674	1.394	1.467	3.546	3.707	3.591	0.404	0.548	0.464	0.617	NS	NS

NS: Non-significant

Table 5: Effect of nano macro and micro nutrients on leaf number and clump characters

Treatments	Leaf number						Clump								
	90 DAP			150 DAP			Weight (g)			Length (cm)			Breadth (cm)		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T ₁	7.02	7.37	7.20	13.26	14.75	14.01	254.31	297.76	276.04	20.37	22.52	21.45	13.17	14.03	13.60
T ₂	8.08	8.65	8.37	15.75	16.07	15.91	313.05	335.20	324.13	22.46	22.23	22.35	13.42	14.94	14.18
T ₃	7.59	7.93	7.76	15.27	15.93	15.60	299.14	350.58	324.86	22.13	23.32	22.73	13.26	15.34	14.30
T ₄	8.61	9.53	9.07	16.56	17.12	16.84	389.23	431.86	410.55	23.52	24.76	24.14	15.76	16.89	16.33
T ₅	7.52	8.13	7.83	14.94	15.04	14.99	317.71	354.13	335.92	21.69	22.97	22.33	14.79	15.44	15.12
T ₆	8.46	8.62	8.54	16.68	16.39	16.54	399.16	410.34	404.75	23.10	23.66	23.38	15.38	17.65	16.52
T ₇	8.04	8.39	8.22	16.74	16.42	16.58	354.60	371.67	363.14	23.28	24.49	23.89	14.75	16.31	15.53
T ₈	9.05	9.27	9.16	16.85	17.26	17.06	428.52	456.27	442.40	24.65	23.93	24.29	16.82	17.11	16.97
S.Em. (±)	0.104	0.114	0.108	0.269	0.232	0.205	4.550	4.846	4.651	0.300	0.305	0.296	0.187	0.204	0.200
C.D. (P=0.05)	0.320	0.349	0.332	0.823	0.711	0.626	13.936	14.840	14.244	0.920	0.933	0.908	0.574	0.625	0.612

Table 6: Effect of nano macro and micro nutrients on primary finger characters

Treatments	Primary finger											
	Number			Weight (g)			Length (cm)			Breadth (cm)		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T ₁	12.56	13.30	12.93	163.36	187.45	175.41	7.64	8.18	7.91	1.69	1.63	1.66
T ₂	13.11	15.56	14.34	209.16	230.56	219.86	7.42	8.26	7.84	1.64	1.88	1.76
T ₃	14.06	15.01	14.54	218.05	226.89	222.47	8.42	8.13	8.28	1.55	1.71	1.63
T ₄	16.34	21.02	18.68	251.63	276.28	263.96	8.37	9.06	8.72	1.96	2.28	2.12
T ₅	12.88	16.19	14.54	198.31	238.55	218.43	7.71	8.21	7.96	1.73	2.01	1.87
T ₆	16.75	20.35	18.55	268.14	248.46	258.30	8.22	8.75	8.49	2.09	1.96	2.03
T ₇	15.58	16.24	15.91	240.43	247.31	243.87	7.75	8.52	8.14	1.81	2.21	2.01
T ₈	17.03	22.30	19.67	279.36	327.72	303.54	8.85	8.73	8.79	2.14	2.32	2.23
S.Em. (±)	0.200	0.233	0.218	3.036	3.278	3.094	0.129	0.111	0.106	0.024	0.027	0.025
C.D. (P=0.05)	0.612	0.713	0.666	9.298	10.039	9.476	0.397	0.341	0.326	0.073	0.082	0.077

Table 7: Effect of nano macro and micro nutrients on secondary finger characters

Treatments	Secondary finger											
	Number			Weight (g)			Length (cm)			Breadth (cm)		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T ₁	7.86	9.40	8.63	60.52	76.81	68.67	3.10	3.79	3.45	1.37	1.51	1.44
T ₂	8.12	8.81	8.47	71.79	65.76	68.78	4.01	3.07	3.54	1.62	1.36	1.49
T ₃	7.53	9.91	8.72	48.53	88.45	68.49	3.18	4.53	3.86	1.25	2.01	1.63
T ₄	9.08	9.74	9.41	90.95	102.08	96.52	4.11	4.56	4.34	1.78	2.12	1.95
T ₅	8.63	9.06	8.85	69.84	70.41	70.13	3.46	3.21	3.34	1.56	1.57	1.57
T ₆	9.11	9.66	9.39	84.28	110.97	97.63	4.29	4.54	4.42	1.95	2.20	2.08
T ₇	8.46	8.79	8.63	73.21	83.60	78.41	3.74	4.48	4.11	1.80	2.26	2.03
T ₈	9.84	9.31	9.58	97.80	115.65	106.73	4.34	4.65	4.50	1.68	1.79	1.74
S.Em. (±)	0.112	0.123	0.118	1.263	1.403	1.299	0.067	0.065	0.065	0.028	0.028	0.028
C.D. (P=0.05)	0.343	0.376	0.362	3.867	4.297	3.979	0.204	0.199	0.199	0.086	0.086	0.086

Table 8: Effect of nano macro and micro nutrients on yield

Treatments	Yield					
	Plot yield (kg 3m ²)			Projected yield (t ha ⁻¹)		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T ₁	9.63	11.50	10.57	24.08	28.76	26.42
T ₂	11.83	12.79	12.31	29.59	31.98	30.78
T ₃	11.50	13.23	12.36	28.74	33.07	30.90
T ₄	13.34	14.05	13.69	33.35	35.12	34.24
T ₅	12.33	13.56	12.95	30.83	33.90	32.37
T ₆	12.90	14.08	13.49	32.25	35.19	33.72
T ₇	13.26	13.60	13.43	33.16	34.00	33.58
T ₈	13.88	14.73	14.30	34.69	36.83	35.76
S.Em. (±)	0.158	0.174	0.167	0.514	0.560	0.412
C.D. (P=0.05)	0.484	0.532	0.510	1.576	1.715	1.263

Table 9: Effect of nano macro and micro nutrients on economics of turmeric

Treatments	Cost of production (Rs. ha ⁻¹)			Gross returns (Rs. ha ⁻¹)			Net returns (Rs. ha ⁻¹)			B:C Ratio		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T ₁	212161	217611	214886	433440	517680	475560	221279	300069	260674	1.04	1.38	1.21
T ₂	211568	217018	214293	532620	575640	554130	321052	358622	339837	1.52	1.65	1.58
T ₃	206016	211466	208741	517320	595260	556290	311304	383794	347549	1.51	1.81	1.66
T ₄	205422	210872	208147	600300	632160	616230	394878	421288	408083	1.92	2.00	1.96
T ₅	211936	217386	214661	554940	610200	582570	343004	392814	367909	1.62	1.81	1.71
T ₆	211342	216792	214067	580500	633420	606960	369158	416628	392893	1.75	1.92	1.83
T ₇	205791	211241	208516	596880	612000	604440	391089	400759	395924	1.90	1.90	1.90
T ₈	205197	210647	207922	624420	662940	643680	419223	452293	435758	2.04	2.15	2.10

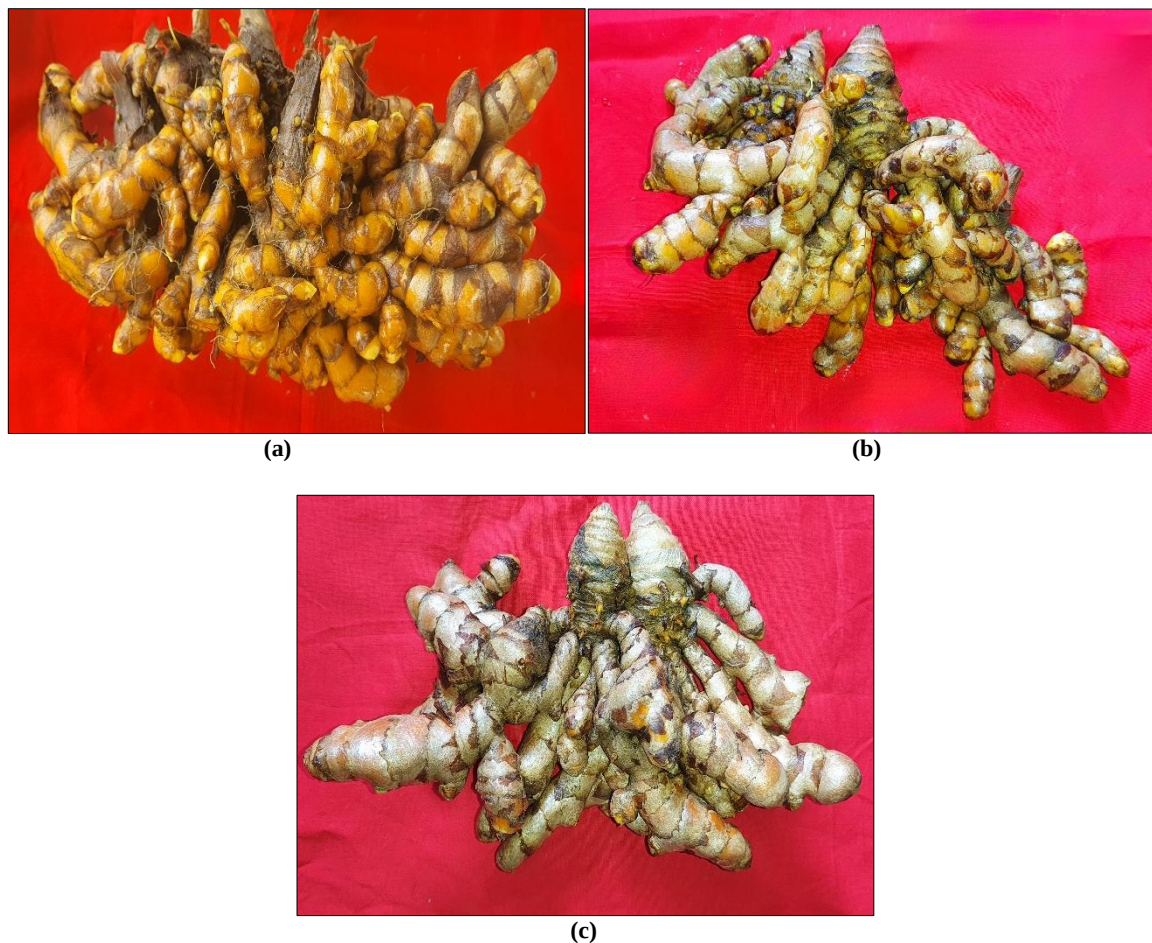


Fig 1: Effect of nano macro and micro nutrients on clump. (a) Clump under T₈. (b) Clump under T₄. (c) Clump under T₁

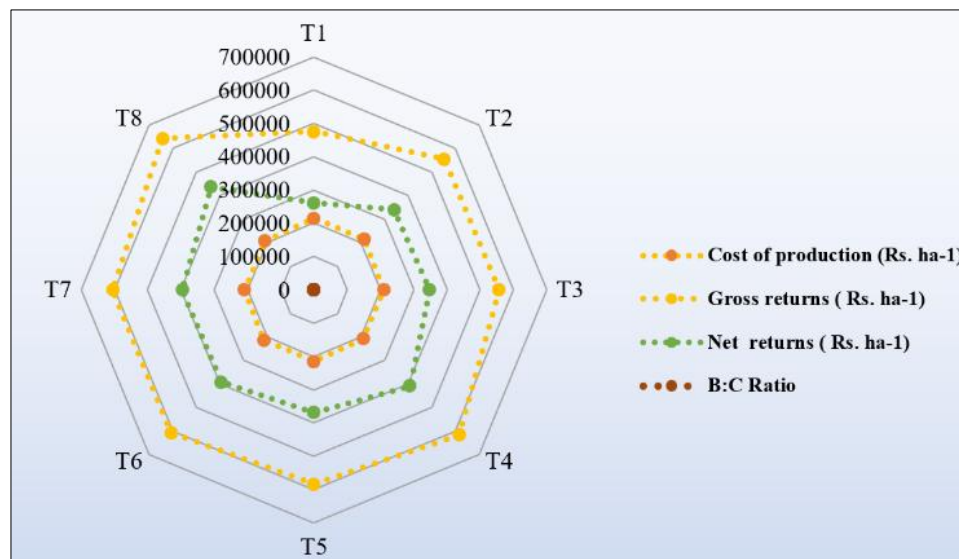


Fig 2: Effect of nano nutrients on economics of turmeric

Discussion

The present investigation clearly demonstrated that integration of nano-formulated macro- (N, P and K) and micronutrients (Zn, Mn and Cu) with reduced conventional fertilizer doses significantly improved the vegetative growth, yield attributes, rhizome yield and economic returns of turmeric. Among all the treatments T₈, comprising 40% basal N and 75% basal P followed by foliar application of nano NPK at 45 DAP, nano NK at 90 DAP and nano Zn, Mn and Cu at 45 and 90 DAP @ 0.4%, recorded better performance for most of the growth and yield parameters.

The findings indicated that judicious integration of nano-fertilizers with conventional fertilizers can substantially enhance nutrient use efficiency while reducing the dependence on bulk fertilizers.

The significant improvement in plant height, tiller production, leaf number and leaf dimensions under T₈ may be attributed to the synchronized supply of essential macro- and micronutrients during critical stages of crop growth (Kalaji *et al.*, 2014) ^[10]. Nitrogen is directly involved in chlorophyll synthesis, amino acid metabolism and

vegetative growth, while phosphorus promotes root development, energy transfer and cell division. Potassium regulates stomatal conductance, enzyme activation, photosynthate translocation and water relations. Simultaneously, zinc, manganese and copper serve as cofactors of numerous enzymes associated with photosynthesis, protein synthesis, antioxidant metabolism and auxin biosynthesis (Johnson and Mirza, 2020) ^[9]. The nano sized formulations possess a larger surface area and greater reactivity, facilitating rapid penetration through leaf tissues, enhanced nutrient absorption and prolonged nutrient availability, thereby improving nutrient use efficiency and minimizing nutrient losses (Semenova *et al.*, 2024) ^[18]. Consequently, plants receiving integrated nano nutrition exhibited greater photosynthetic capacity and assimilate production, which ultimately promoted vigorous vegetative growth.

The superior vegetative performance obtained with nano-fertilizer application corroborates previous findings in several horticultural crops. Manikanta *et al.* (2023) ^[13] reported that foliar application of nano nitrogen, zinc and copper liquid fertilizers @ 0.4% significantly enhance the plant height, branching and leaf production in potato. Likewise, Garg (2024) ^[6] observed that application of 80% of RDF along with 3 spray of nano N, P, K, Zn and Fe @ 0.5% resulted marked improvement in vegetative growth of garlic with integrated application of nano NPK, Zn and Fe along with reduced recommended fertilizer doses. Similar responses have also been documented by Badawy *et al.* (2025) ^[2], who attributed increased plant growth in zinnia to enhanced nutrient availability and physiological efficiency due to foliar spraying of nano-NPK @ 4 ml L⁻¹, and NPK + nano micro-nutrients @ 4 ml L⁻¹ increased the number of branches per plant in zinnia. These reports collectively support the present findings that nano-fertilizers effectively improve crop growth by increasing nutrient uptake efficiency and metabolic activity.

The enhanced clump characteristics, primary and secondary finger development and rhizome yield observed under T₈ were largely a consequence of improved vegetative growth and efficient partitioning of photosynthates towards developing rhizomes. Increased leaf area and tiller production enhanced light interception and photosynthetic efficiency, thereby increasing carbohydrate synthesis. Adequate potassium supply through nano formulations likely facilitated efficient translocation of assimilates from source leaves to sink organs, while phosphorus supported ATP production and energy-dependent metabolic processes required for rhizome initiation and enlargement (Kubavat *et al.*, 2020) ^[11]. Zinc further promotes endogenous auxin synthesis, manganese plays a vital role in photosynthetic oxygen evolution and enzyme activation, and copper contributes to respiratory metabolism and lignification, collectively enhancing sink strength and rhizome development (Seleiman *et al.*, 2020) ^[17]. The combined action of these nutrients therefore resulted in greater biomass accumulation and improved rhizome architecture. The improvement in rhizome characteristics due to combined application of nano macro and micro nutrients corroborates previous study of Neogi and Das (2022) ^[16] who observed that nano-nitrogen and zinc significantly

promoted bulb characteristics by improving micronutrient bioavailability and physiological performance in potato.

The higher rhizome yield recorded under integrated nano nutrient management further indicates that foliar application of nano-fertilizers can effectively supplement soil-applied fertilizers during periods of high nutrient demand. Foliar applied nanoparticles are rapidly absorbed and translocated within plant tissues, enabling timely nutrient availability with minimal fixation losses commonly associated with soil-applied fertilizers, particularly phosphorus (Liu and Lal, 2014) ^[12]. This synchronized nutrient delivery likely maintained optimum physiological activity throughout crop growth, thereby maximizing rhizome productivity. Comparable improvements in yield due to application of nano-macro and micro nutrients have been reported by Manikanta *et al.* (2023) ^[13] in potato, Garg (2024) ^[6] in garlic and Hamed *et al.* (2025) ^[8] in sugar beet.

Economic analysis shows that the inclusion of nano-fertilizers marginally increased the cost of cultivation in some treatments, the substantial increase in rhizome yield resulted in markedly higher gross returns, net returns and benefit-cost ratio under T₈. The greater economic advantage primarily arose from higher marketable yield rather than increased production costs, indicating that the investment in nano-fertilizers was economically justified. Furthermore, partial substitution of conventional fertilizers with nano formulations reduced the quantity of bulk fertilizers required while maintaining or enhancing crop productivity, thereby improving input use efficiency and overall profitability. These findings suggest that integrated nano nutrient management represents a sustainable and economically viable strategy for commercial turmeric cultivation.

Conclusion

The present study demonstrates that combining nano-formulated macro- and micronutrients with optimized conventional fertilizer application improved vegetative growth, superior rhizome development and higher yield. Considering the growth parameters, projected yield and B:C ratio the treatment combinations of 40% N + 75% P as basal → 0.4% nano N, P and K at 45 DAP → 0.4% nano N and K at 90 DAP + 0.4% nano Zn + Mn + Cu at 45 and 90 DAP (T₈) was identified as the most effective for turmeric cultivation, followed by 40% N + 100% P as basal → 0.4% nano N + K + Zn + Mn + Cu at 45 and 90 DAP (T₄). The better performance of T₈ highlights the importance of synchronizing foliar nano nutrient application with crop nutrient demand to maximize productivity and profitability in turmeric cultivation.

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Author's contribution

Field experiment, laboratory analysis, preparation of manuscript and manuscript edit (AS).

Helped in laboratory and field data recording (AS) and (US).

Conceptualization of research work and methodology, manuscript reviewed (JKH).

Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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