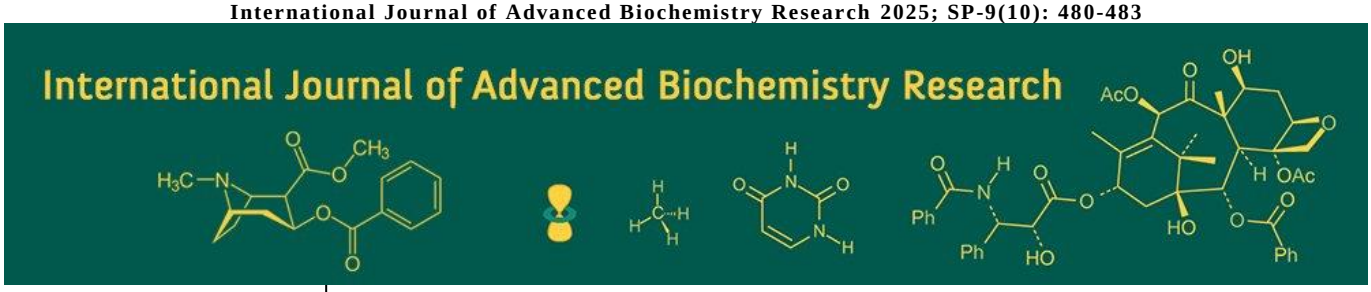

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Performance of Nano formulations under graded levels of nitrogen and phosphorus in chilli (*Capsicum annuum* L.)

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Abstract
The experiment was carried out at Dr.YSRHU- Regional Horticulture Research Station, Lam, Guntur - 522034, Andhra Pradesh from September 2024 to May 2025 Factorial Randomized Block Design comprising fifteen treatment combinations replicated thrice with two factors i.e., nutrients levels at three *viz*., 75% RNP, 100% RNP, 125% RNP and foliar nutrition at five levels i.e., foliar nutrition each sprayed at (75, 100 and 125 DAP). All the parameters pertaining to growth, yield were recorded and analysed as per the standard procedures. Among nutrient levels 125% RNP (N_3) performed best with respect to growth, yield, *viz*., plant height (102.40 cm), number of branches per plant (15.31),number of fruits per plant (210.02), fruit yield per plant (164.63 g), fruit yield per hectare (44.41q/ha), Fruit length (12.41 cm). Among foliar nutrition F_4 (Nano Urea + Nano DAP @ 5 mL L^{-1}) foliar nutrition each sprayed at 75, 100, 125 DAP performed best with respect to growth, yield parameters, *viz*., plant height (104.80 cm), number of branches per plant (15.37), number of fruits per plant (217.01), fruit yield per plant (180.89 g), fruit length (12.77 cm), fruit yield per hectare (47.11 q/ha), Among the interaction (N_3F_4), 125% RNP (Nano Urea + Nano DAP @ 5 mL L^{-1}) foliar nutrition each sprayed at 75, 100, 125 DAP shows best results in plant height (109.43 cm), number of branches per plant (15.62 cm), Fruit length (13.33 cm), and (N_2F_4) 100% RNP (Nano Urea + Nano DAP @ 5 mL L^{-1}) foliar nutrition each sprayed at 75, 100, 125 DAP shows best results in number of fruits per plant (228.23), fruit yield per plant (198.93 g), fruit yield per hectare 49.79 q/ha).

Keywords: Nutrient management, foliar nutrition, Nano fertilizers, growth and yield

1. Introduction
Chilli (*Capsicum annuum* L.), belonging to the family Solanaceae (2n = 24), is one of the most widely cultivated vegetable and spice crops across tropical and subtropical regions. Originally discovered by Christopher Columbus in Tropical America, its primary center of origin is Mexico, with secondary centers in Guatemala and Bulgaria (Salvador, 2002) [11]. The genus Capsicum comprises five major cultivated species *C. annuum, C. frutescens, C. baccatum, C. pubescens, and C. chinense*. Introduced to India by Portuguese traders in the late 15th century, chilli quickly became integral to Indian cuisine due to its pungency from capsaicin and its diverse commercial forms such as powder, paste, and oleoresin.
Chilli is an annual shrub reaching up to 1.5 m in height, predominantly self-pollinated, though open pollination may lead to 7-36% cross-pollination (Davenport, 2004) [2]. It thrives in well-drained loam soils with a pH of 6.5-7.5 and moderate salinity tolerance.
Globally, over 400 types of chillies are cultivated, with India being the largest producer, importer, and exporter, contributing around 42% of global exports. In India, Andhra Pradesh leads production with 14.44 lakh tonnes (49.57%), followed by Telangana and Karnataka (Crop Outlook Reports, ANGRAU, 2024) [1]. The Guntur Chilli Yard, Asia's largest, plays a pivotal role in global chilli pricing.
Chilli is valued for its flavor, color, vitamins (A, C, E), and minerals, as well as for oleoresin used in food and beverage industries. Capsaicin, bioactive alkaloid acts as a digestive stimulant and therapeutic compound against rheumatism. However, the excessive use of chemical fertilizers has led to soil degradation, heavy metal accumulation, and reduced yields.

In recent years, Nanotechnology has emerged as a sustainable solution in agriculture, offering precise and efficient nutrient delivery. Nano-formulations such as Nano Urea and Nano DAP (<100 nm particle size) enhance nutrient absorption, utilization efficiency, and minimize losses (Kantwa & Yadav, 2022) [3]. Their application in chilli cultivation has shown superior performance over conventional fertilizers in improving growth, yield, and quality (Kumar *et al.*, 2023) [4].

2. Materials and methods: The experiment was conducted during the *Kharif* season, spanning from 2024 to 2025, at the Dr. Y.S.R. Horticultural Research Station, Lam, Guntur District, Andhra Pradesh, India. The site falls under Agro-climatic Zone-10, specifically the humid East Coast Plain and Hills (Krishna-Godavari zone) and Followed Factorial Randomized Block Design (FRBD) with three replicitions examine the Chilli Variety LCA- 643. The 15 treatments are (N_1F_1) 75% RNP Control (Water Spray), (N_1F_2) 75% RNP Nano Urea @ 5 mL L^{-1} at 75,100,125 DAP, (N_1F_3) 75% RNP Nano DAP @ 5 mL L^{-1} at 75,100,125 DAT, (N_1F_4)75% RNP Nano Urea + Nano DAP @ 5 mL L^{-1} each at 75,100,125 DAP, (N_1F_5) 75% RNP Urea 20g + DAP 20g per litre at 75,100,125 DAP, (N_2F_1) 100% RNP, Control (Water Spray), (N_2F_2) 100% RNP Nano Urea @ 5 mL L^{-1} at 75,100,125 DAP, (N_2F_3) 100% RNP Nano DAP @ 5 mL L^{-1} at 75,100,125 DAT, (N_2F_4) 100% RNP Nano Urea + Nano DAP @ 5 mL L^{-1} each at 75,100,125 DAP, (N_2F_5) 100% RNP Urea 20g + DAP 20g per litre at 75,100,125 DAP, (N_3F_1) 125% RNP Control (Water Spray), (N_3F_2) 125% RNP Nano Urea @ 5 mL L^{-1} at 75,100,125 DAP, (N_3F_3) 125% RNP Nano DAP @ 5 mL L^{-1} at 75,100,125 DAT, (N_3F_4) 125% RNP Nano Urea + Nano DAP @ 5 mL L^{-1} each at 75,100,125 DAP, (N_3F_5) 75% RNP Urea 20g + DAP 20 g per litre at 75,100,125 DAP

3. Results and discussion

3.1 Plant height at 100 DAP and harvest (cm)

Plant height at 100 DAP was significantly influenced by nutrient levels, foliar nutrition, and their interaction. Basal application of 125% RNP (N_3) the maximum mean height of 72.09 cm, superior to N_2 (67.60 cm) and the minimum N_1 (62.34 cm). Among foliar treatments, F4 (Nano Urea + Nano DAP) produced the highest mean height of 73.01 cm, followed by F5 (69.02 cm), significantly exceeding the control (F_1) at 62.88 cm. The interaction resulted in the maximum height of 76.22 cm under N_3F_4 (125% RNP+Nano foliar), which was statistically on par with several high-performing combinations, including N_3F_5, N_3F_1 (70.16 cm), N_3F_2 (71.92 cm), N_3F_3 (72.30 cm), and N_2F_4 (72.00 cm). The minimum height was recorded in the absolute control N_1F_1 at 54.92 cm.

Plant height at harvest was significantly influenced by nutrient levels, foliar nutrition, and their interaction. Basal application of 125% RNP (N_3) produced the maximum mean height of 102.40 cm, followed by N_2 (95.74 cm), Foliar application of Nano Urea + Nano DAP (F_4) resulted in the highest mean height of 104.80 cm, substantially exceeding the control (F_1) at 87.85 cm. The interaction resulted in the absolute maximum plant height of 109.43 cm under N_3F_4 (125% RNP + Nano Urea + Nano DAP), which was statistically on par with N_2F_4 (106.63 cm) and N_3F_5 (104.25 cm). This superior growth is attributed to the synergy between soil-applied fertilizers and high-efficiency Nano-nutrients, which, due to their small size, facilitate rapid absorption and enhance metabolic activities like cell division and elongation, thereby maximizing plant stature, consistent with findings in chilli (Neeruggi *et al.*, 2024; Maske *et al.* 2025) [9, 6] and cucumber (Merghany *et al.*, 2019) [7].

3.2 Number of branches per plant 100 DAP and at harvest: The number of branches per plant at 100 DAP was significantly influenced by nutrient levels, foliar nutrition, and their interaction. Among the basal nutrient levels, 125% RNP (N_3) produced the maximum mean number of branches at 7.74, closely followed by N_2 (100% RNP) at 7.40, confirming that ample nutrient supply supports vigorous vegetative growth. Foliar nutrition further enhanced branching, with the F_4 treatment (Nano Urea + Nano DAP) yielding a mean of 7.91 branches, which was superior to the control (F_1) at 6.89. The interaction effect was most notable: the N_2F_4 combination (100% RNP +Nano foliar) achieved the absolute maximum number of branches at 8.16, and this result was statistically on par with N_3F_4 (8.03). The minimum branch count was observed in the control N_1F_1 at 6.63, emphasizing the synergistic benefit of combining an optimal basal dose with high-efficiency Nano-foliar nutrition.

The number of branches per plant at harvest was significantly influenced, among basal levels, 125% RNP (N_3) produced the maximum mean branches at 15.31, followed closely by N_2 (100% RNP) at 14.81, importance of ample N and P for vegetative growth. Foliar application of Nano Urea + Nano DAP (F_4) resulted in the highest mean branch count of 15.37, significantly exceeding the control (F_1) at 14.02. The maximum branch count was recorded in the interaction N_3F_4 at 15.62, a result statistically on par with N_3F_3 (15.41), N_2F_3 (15.36), and N_2F_4 (15.34). This superior branching is attributed to the highly efficient supply of N and P from the combined Nano and conventional fertilizers, which maximizes metabolic activity and strongly stimulates axillary bud production, thereby driving extensive canopy development, a finding consistent with Mishra *et al.* (2020) [8] and Neeruggi *et al.* (2024) [9].

3.3 Number of fruits per plant

The number of fruits per plant was significantly influenced by nutrient levels, foliar nutrition, and their interaction, with sprays applied at 75, 100, and 125 DAP being effective. Higher nutrient levels generally increased fruit count, with the maximum mean number of 206.79 fruits observed in N_3 (125% RNP), which was superior to N_1 (75% RNP) at 188.16 fruits. Foliar application of Nano Urea + Nano DAP (F_4) delivered the highest mean fruit count of 217.01, significantly surpassing the water spray control (F_1) at 183.99. The optimal combination, N_2F_4 (100% RNP+Nano Urea + Nano DAP @ 5 mL L^{-1}), achieved the absolute maximum of 228.2 fruits, which was statistically on par with N_3F_4 (218.33 fruits). This exceptional synergy is attributed to the optimized nutrient strategy where readily available N and P maximize DNA and protein synthesis, thereby aggressively promoting floral induction and successful fruit set, aligning with the findings of Neeruggi *et al.* (2024) [9].

3.4 Fruit yield per plant (g): Significantly based on nutrient levels, foliar nutrition, and their interaction.

Maximum mean yield was achieved with 125% RNP (N_3) at 164.73g, closely followed by 100% RNP (N_2) at 161.65g, confirming the critical role of adequate N, P, and K for fruit development. Foliar application of Nano Urea + Nano DAP (F_4) resulted in the maximum yield of 180.89 g, significantly exceeding the water spray control (F_1) yield of 143.08 g. The optimal interaction, N_2F_4 (100% RNP +Nano foliar), produced the highest dry fruit yield of 198.93 g, which was statistically on par with N_3F_4 (188.15 g). The minimum yield (129.15 g) was recorded in the control N_1F_1. This superior yield from the N_2F_4 combination is attributed to improved nutrient uptake and mobilization, enhanced chlorophyll content, increased photosynthetic efficiency, and optimal metabolite partitioning to the fruit sinks, leading to increased fruit retention and weight. (Mishra *et al.*, 2020) [8].

3.5 Fruit Length (cm)

The analysis of fruit length showed significant main effects and interaction. The highest mean fruit length was observed in N_3 (125% RNP at 12.10 cm), statistically on par with N_2 (12.16 cm), indicating that increased soil nutrition enhances physiological development. Among foliar treatments, F_4 (Nano Urea + Nano DAP at 5 mL L^{-1}) produced the longest mean fruit length of 12.77 cm, demonstrating that the combined foliar nutrition optimizes nutrient uptake and stress tolerance. The maximum fruit length of 13.33 cm was recorded under the optimal interaction N_3F_4 (125% RNP +Nano Urea +Nano DAP), which was statistically on par with N_2F_4 (13.23 cm), highlighting the synergy between high basal and targeted foliar nutrition. This superior fruit size is mechanistically linked to the dual-action supply of N and P, which drives rapid cell division and enlargement, maximizing dry matter accumulation, optimizing water content, and enhancing the diversion of photo-assimilates to the developing fruit, consistent with findings by Neeruggi *et al.* (2024) [9] and Kumawat *et al.* (2025) [5].

3.6 Fruit yield per hectare (q ha^{-1})

The analysis of fruit yield per hectare revealed significant effects from both nutrient levels and foliar nutrition, with the interaction. The 125% RNP (N_3) level achieved a superior mean yield of 41.33 q ha^{-1}, requirement for sufficient N, P, and K. Foliar application of Nano Urea + Nano DAP (F_4) resulted in the maximum mean yield of 49.07 q ha^{-1}, markedly outperforming the water spray control (F_1) yield of 37.09 q ha^{-1}. The peak yield was obtained from the highly significant interaction N_2F_4 at 49.79 q ha^{-1}. This result that maximum productivity relies on a synergistic relationship where the 100% RNP (N_2) fulfills the basal requirement, and the F_4 treatment acts as a precise yield booster during the reproductive phase, maximizing Nutrient Use Efficiency. Panda *et al.* (2020) [10].

Table 1: Effect of Nano and conventional fertilizers on plant height (cm)

	100 days after planting						at harvest					
	F_1	**F_2**	**F_3**	**F_4**	**F_5**	**Mean**	**F_1**	**F_2**	**F_3**	**F_4**	**F_5**	**Mean**
N_1	54.92	58.22	62.37	70.38	65.81	62.34	81.30	84.69	91.31	98.34	96.19	90.37
N_2	63.56	66.38	67.24	72.00	68.85	67.60	87.96	95.47	91.07	106.63	97.57	95.74
N_3	70.16	71.92	72.30	73.65	72.41	72.09	94.29	100.43	103.58	109.43	104.25	102.40
Mean	62.88	65.51	67.30	72.01	69.02		87.85	93.53	95.32	104.80	99.34	
Factors	SE m ±			CD at 5%			SE m ±			CD at 5%		
N	0.43			1.26			0.70			2.05		
F	0.56			1.62			0.91			2.65		
N X F	0.97			2.81			1.57			4.58		

Table 2: Effect of Nano and conventional fertilizers on plant spread (cm)

	100 days after planting						at harvest					
	F_1	**F_2**	**F_3**	**F_4**	**F_5**	**Mean**	**F_1**	**F_2**	**F_3**	**F_4**	**F_5**	**Mean**
N_1	47.27	50.17	52.40	53.47	52.60	51.18	72.68	80.50	83.14	84.44	83.70	80.89
N_2	49.84	51.41	54.50	56.20	52.10	52.81	80.41	82.24	83.55	87.57	84.77	83.71
N_3	48.40	53.40	55.70	57.80	54.01	53.87	81.40	83.80	84.08	89.34	85.11	84.75
Mean	48.51	51.66	54.20	55.83	52.91		78.16	82.18	83.59	87.12	84.53	
Factors	SE m ±			CD at 5%			SE m ±			CD at 5%		
N	0.27			0.79			0.51			1.49		
F	0.35			1.02			0.66			1.92		
N X F	0.61			1.76			1.14			3.33		

Table 3: Effect of Nano and conventional fertilizers on number of fruits per plant

	Number of Fruit per plant					
	F_1	**F_2**	**F_3**	**F_4**	**F_5**	**Mean N**
N_1	159.53	177.73	196.13	202.13	205.27	188.16
N_2	195.17	200.13	198.13	228.23	212.30	206.79
N_3	197.27	202.17	211.67	220.67	218.33	210.02
Mean F	183.99	193.35	201.98	217.01	211.97	
	SEm±			C.D. at 5%		
N	1.51			4.40		
F	1.95			5.68		
NXF	3.38			9.84		

Table 4. Effect of Nano and conventional fertilizers on fruit yield per plant

	Fruit yield per plant (g)					
	F_1	**F_2**	**F_3**	**F_4**	**F_5**	**Mean N**
N_1	129.15	144.99	151.50	155.58	154.59	147.16
N_2	146.44	150.44	153.26	198.93	159.18	161.65
N_3	153.64	154.75	161.56	188.15	165.55	164.73
Mean F	143.08	150.06	155.44	180.89	159.77	
	SEm±			C.D. at 5%		
N	1.74			5.08		
F	2.25			6.56		
NXF	1.74			11.36		

Table 5. Effect of Nano and conventional fertilizers on fruit length (cm)

	Fruit length (cm)					
	F_1	**F_2**	**F_3**	**F_4**	**F_5**	**Mean N**
N_1	11.50	11.73	11.83	11.73	11.33	11.63
N_2	11.83	11.50	12.13	13.23	12.10	12.16
N_3	11.67	12.53	12.40	13.33	12.10	12.41
Mean F	11.67	11.92	12.12	12.77	11.84	
	SEm±			C.D. at 5%		
N	0.10			0.29		
F	0.13			0.37		
NXF	0.22			0.65		

Table 6. Effect of Nano and conventional fertilizers on fruit yield (q ha^{-1})

	Fruit yield per (q ha^{-1})					
	F_1	**F_2**	**F_3**	**F_4**	**F_5**	**Mean N**
N_1	35.57	38.76	40.24	43.78	43.41	40.35
N_2	36.98	39.17	41.69	49.79	43.38	42.21
N_3	41.33	43.17	44.83	47.76	44.95	44.41
Mean F	37.96	40.37	42.25	47.11	43.91	
	SEm±			C.D. at 5%		
N	0.40			1.15		
F	0.51			1.49		
NXF	0.89			2.58		

4. Conclusion

The present investigation conclusively demonstrates that both 125% RNP and foliar nutrition treatment F_4 (Nano Urea + Nano DAP @ 5 mL L^{-1} each, sprayed at 75, 100, and 125 DAP) showed promising effects on plant growth parameter. Crucially, the combination of 100% RNP (Nano Urea + Nano DAP @ 5 mL L^{-1} each, sprayed at 75, 100, and 125 DAP consistently resulted in superior yield and quality parameters compared to the control treatments. Therefore, the integrated nutrient management strategy of applying 100% RNP supplemented with foliar F_4 is highly recommended for the commercial cultivation of chilli due to its maximized efficiency and productivity.

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