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Enhancing the Productivity and Economic Feasibility of Transplanted Rice (*Oryza sativa* L.) Through Foliar Application of Nano Fertilize

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

One of the world's most important field crops, rice (*Oryza sativa* L.) is a staple diet for millions of people and is ranked second only to wheat. In Asia, rice consumption is projected to increase by over 51% by 2025 compared to the base year 1995. To sustain the growing population while

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considering environmental health, soil health, and the economic well-being of farmers, nano fertilizers could serve as an ideal alternative to traditional chemical fertilizers. Keeping this in mind a field experiment was conducted during the Kharif season of 2019-2020 at the Main Experimental Station of Acharya Narendra Deva University of Agriculture & Technology, Kumarganj, Ayodhya (U.P.), to evaluate the impact of foliar application of nano fertilizers on transplanted rice. The experiment aimed to compare different fertilizer treatments on rice productivity, nutrient uptake, and economic returns. Six treatments were tested, including T_0 (Control), T_1 (100% NPK & 100% Zinc application - RDF), T_2 (50% N, 100% P & K + 2 sprays of Nano Nitrogen), T_3 (0% Zn, 100% NPK + 2 sprays of Nano Zinc), T_4 (50% N & 0% Zn, 100% P & K + 2 sprays of Nano N mixed with Nano Zn), and T_5 (50% N & 0% Zn, 100% P & K + 2 sprays of Nano N mixed with Nano Zn & Nano Cu), arranged in a Randomized Block Design with four replications. The results revealed that the highest grain yield was recorded in T_5, which involved the foliar application of Nano Nitrogen (Nano N), Nano Zinc (Nano Zn), and Nano Copper (Nano Cu) with 50% nitrogen (N) and 0% zinc (Zn), along with 100% phosphorus (P) and potassium (K). This treatment produced a yield that was statistically comparable to T_4 (50% N & 0% Zn, 100% P & K + 2 sprays of Nano N mixed with Nano Zn) and T_3 (0% Zn, 100% NPK + 2 sprays of Nano Zinc). Treatment T_5 also yielded the highest gross return (Rs. 119,841 ha^{-1}), net return (Rs. 64,711 ha^{-1}), and benefit-cost ratio (2.17). Additionally, the nitrogen (%), phosphorus (%), potassium (%), copper (%), and zinc (ppm) contents in both the grain and straw were significantly higher under T_5. These findings suggest that the foliar application of Nano N, Nano Zn, and Nano Cu in combination with reduced nitrogen and zinc can enhance nutrient uptake and improve the overall productivity and profitability of rice cultivation in central Uttar Pradesh.

Keywords: Nano-fertilizer; productivity; profitability; foliar application; economic feasibility; harvest index.

1. INTRODUCTION

"Rice, the world's most important food crop, is the staple food for about four billion people i.e., half of the humankind on the planet. Rice fields cover around 160 million hectares (Mha) in a wide range of climatic conditions spanning from 44 N in North Korea to 35 S in Australia. It is cultivated from six feet below sea level (such as in Kerala, India) to 2700 feet above sea level in the Himalayas. The crop occupies a significant position in the culture and heritage of many Asian countries. In Asia, rice consumption by the year 2025, over the base year 1995, will increase by more than 51 per cent (Papademetriou, 2024). Globally, during 2022-23, the area, production, and productivity of rice were 165.70 million hectares (mha), 512.98 million metric tons (mmt), and 46.20 quintals per hectare (q ha^{-1}), respectively. India ranked first in terms of rice cultivation area and second in production, with 47.83 mha and 135.76 mmt, respectively. However, India's crop productivity of 42.60 q ha^{-1} lags behind the global average of 46.20 q ha^{-1}, as well as 82.80 q ha^{-1} in the United States and 70.8 q ha^{-1} in China [Verma et al., 2024; USDA, 2022]. Rice is a staple food for about 800 million people in India. It plays a major role in diet, economy, employment, culture and history" (Pathak, et al., 2020). "India is the second-largest rice-growing country and has the highest area under rice cultivation (~43 million ha) in the world" (Guha et al., 2021; India at a Glance, Food and Agriculture Organization of the United Nations, India, 2024). Rice contributes more than 40% of India's total food grain production. In 2019–2020, the area under rice cultivation was 43.7 million ha, with a total production of 118.4 million tonnes and average productivity of around 2,705 kg/ha. "Kharif (summer monsoon) rice has a significant share in total rice production in India. In 2019–2020, the Kharif rice production was estimated to be 102.4 million tonnes" (Guha et al., 2021). Uttar Pradesh, with a population of 237 million, is the largest agrarian state in India, located in the Indo-Gangetic plains. "Rice cultivation is widespread across all districts of Uttar Pradesh, which have varying climate regimes, irrigation infrastructures, crop management practices, and farm sizes" (Singh, et al., 2024). Rice is the most crucial food crop globally, acting as the main source of nutrition for around four billion individuals, which is nearly half of the world's population. It holds a significant position in the cultural and historical significance of numerous Asian countries and is essential to the economy, employment, and dietary practices of these regions. Worldwide, rice is cultivated across approximately 160 million hectares, thriving in various climatic conditions from 44°N in North Korea to 35°S in Australia. It is grown at altitudes ranging from six feet below sea level in Kerala, India, to 2,700 feet in the Himalayas. "In India specifically, rice is a staple for about 800 million people, underscoring its importance in the country's diet and livelihoods" (Pathak et al*.,*2020). "India ranks as the second-largest producer of rice globally and is notable for having the most significant area devoted to its cultivation, roughly 43 million hectares". (Guha et al*.,* 2021; FAO, 2024) Rice accounts for over 40% of India's total food grain yield. In the 2019–2020 period, the area devoted to rice farming hit 43.7 million hectares, producing a total of 118.4 million tonnes, with an average yield of approximately 2,705 kg/ha. "A large portion originates from Kharif (summer monsoon) rice, which was estimated to be around 102.4 million tonnes during that time" (Guha et al*.,* 2021). Uttar Pradesh, with a population of 237 million and located in the fertile Indo-Gangetic plains, is the largest agricultural state in India. "Rice farming occurs in every district of Uttar Pradesh, despite differences in climate, irrigation facilities, farming practices, and land sizes" (Singh et al*.,* 2024). While fertilizers enhance agricultural productivity, overuse of chemical substances can damage soil, pollute water sources, and jeopardize long-term food security. Traditional farming practices often lead to significant nutrient losses and environmental harm. A critical challenge lies in increasing the current annual rice production of 524 million tonnes to 700 million tonnes by 2025, all while utilizing less land, fewer workers, reduced water resources, and fewer pesticides (Papademetriou, 2024). Conventional fertilizers, while widely accessible, have relatively low nutrient use efficiency and contribute to significant environmental issues such as eutrophication, greenhouse gas emissions, nitrate contamination, and soil pollution (Sahoo et al., 2024). In the current context, nanotechnology, an emerging and transformative field of science and technology, offers groundbreaking opportunities for research in agriculture and biotechnology. With their smaller particle size and larger surface area, nano fertilizers are readily absorbed by plants, increasing dry matter for photosynthesis and ultimately improving crop yield [Verma et al., 2024; Pandey, 2018]. Nanofertilizers present a sustainable alternative by improving nutrient absorption, controlling release rates, and facilitating targeted delivery, which in turn decreases chemical dependency and environmental damage. "Shifting towards nanotechnology-based approaches fosters sustainable agriculture and secures future food supply" (Yadav et al*.,* 2023). Nano fertilizers provide an environmentally sustainable approach to fulfill plant nutritional requirements, increase farmers' profitability, and sustain crop yields while fostering environmental health. Nanotechnology utilizes materials ranging from 1 to 100 nm, allowing for effective nutrient delivery thanks to their large surface area, absorptive capacity, and controlled release properties. IFFCO's Nano Biotechnology Research Centre (NBRC) in Kalol, Gujarat, has created nano urea, zinc, and copper fertilizers, marketed as IFFCO Nano Urea, Nano Zinc, and Nano Copper. "Traditional nutrient application frequently encounters challenges with plant uptake efficiency, leading to pollution of the environment" (Abou El-Nour 2002; Schwab et al. 2015). "Conversely, foliar application proves to be more efficient in addressing nutrient deficiencies, boosting crop yields, and reducing soil fertilizer application, thereby improving nutrient use efficiency". (Roemheld and El-Fouly, 1999; Semidaet al*.,* 2021) Nano fertilizers function as advanced delivery systems, ensuring that nutrients are supplied to plants at the most effective times and locations. They enhance crop yields even when applied in smaller quantities, boost tolerance to abiotic stress, and help reduce heavy metal toxicity. The launch of IFFCO Nano Urea (liquid), now marketed under FCO-1985, signifies a major progress in sustainable agricultural practices. Key features of nano-fertilizers noted in Guru et al. (2015) include: (1) supplying the appropriate nutrients to promote plant growth via soil and foliar applications; (2) being cost-effective and sustainable sources of nutrients for plants; (3) exhibiting high fertilization efficiency; and (4) playing a vital role in pollution reduction. In addition, nano fertilizers—also known as innovative fertilizer alternatives—contribute to decreasing water pollution. Considering these aspects, the objective of the present study was to assess the positive impacts of foliar spraying nano fertilizers (nano-urea (nano-N), nano-Zn, and nano-Cu) on agricultural productivity, nutrient uptake, and economic feasibility with respect to transplanted rice.

2. MATERIALS AND METHODS

A field study was conducted during the Kharif season of 2019-20 at the Main Experimental Station of Acharya Narendra Deva University of Agriculture & Technology (ANDUA&T) in Kumarganj, Ayodhya (U.P.), to investigate [insert study title]. The experimental site is situated in the central Gangetic plain region of Uttar Pradesh, with geographical coordinates between latitudes 24°47' and 26°56' N and longitudes 82°12' and 83°98' E, at an elevation of 113 meters above sea level. During the crop growing period, total rainfall amounted to 69.2 mm, compared to the average annual rainfall of approximately 800 mm. At the time of sowing, the available moisture in the soil profile (100 cm depth) was recorded at 282.5 mm. The soil at the experimental site was slightly neutral, with a pH of 7.7, an electrical conductivity of 0.36 dS m^{-1}, a permanent wilting point of 6.3%, a field capacity of 18.4%, and a maximum water-holding capacity of 29.5%. The bulk density was 1.46 Mg m-3, the particle density was 2.56 Mg m^{-3}, and the porosity was 42.9%. The soil contained 16.3 kg/ha of available P_2O_5 and 154.7 kg/ha of available K_2O. The recommended nutrient dosage was 100:60:40 kg ha^{-1} of N, P_2O_5 and K_2O, with a foliar spray application of nano fertilizers: urea at 4 ml per liter, and both Nano-Zn and Nano-Cu at 2 ml per liter of water, using 500 liters of water per hectare. The fertilizers applied included Urea, DAP, Muriate of Potash (MOP), Zn, and nano fertilizers (nano-nitrogen, zinc, and copper). The experimental crop was the NDR-359 rice variety, transplanted with a spacing of 20 cm between rows and 15 cm between plants. A randomized block design (RBD) was used, with four replications and several treatments. The plots were laid out with gross plot dimensions of 5.25 m x 4.25 m and net plot dimensions of 5 m x 4 m. The treatments were as follows: T_0 (control), T_1 (100% NPK & 100% Zinc application, RDF), T_2 (50% N, 100% P & K with two sprays of Nano Nitrogen), T_3 (0% Zn, 100% NPK with two sprays of Nano Zinc), T_4 (50% N & 0% Zn, 100% P & K with two sprays of Nano N mixed with Nano Zn), and T_5 (50% N & 0% Zn, 100% P & K with two sprays of Nano N mixed with Nano Zn & Nano Cu). Soil samples were collected at different depths before transplantation and after harvesting to assess nutrient availability, while plant samples were analyzed for nutrient content (N, P, K) using standard protocols. Data on yield, growth attributes, nutrient uptake, and economic feasibility were also collected. The rice crop harvested from the net plot area of each treatment was sun-dried, threshed, and cleaned, and the grain yield was recorded at a moisture level of 12%. The straw yield was calculated by subtracting the grain yield from the total biological yield.

Statistical analysis was performed using the mean values, following the methods outlined by Panse and Sukhatme (1978). The experimental data were subjected to analysis of variance (ANOVA) using Fisher's approach (Fisher & Yates, 1958), with a significance level set at p = 0.05 for both the F and t-tests. Critical difference values were computed when the F-test indicated significant results.

3. RESULTS AND DISCUSSION

3.1 Yield and Yield Attribute

The data regarding yield attributes such as grain yield, straw yield, biological yield, and harvest index (displayed in Table 1 & Fig. 1(A)) was found to be higher in treatment T_5, which included 50% nitrogen and 0% zinc, along with 100% phosphorus and potassium, and two applications of Nano N combined with Nano Zn and Nano Cu. However, it showed similar results to treatment T_4, which involved 50% nitrogen and 0% zinc, 100% phosphorus and potassium, plus two sprays of Nano N mixed with Nano Zn. This might be attributed to the foliar application of Nano-fertilizers during critical growth stages, which could provide an adequate supply of nutrients. These nutrients improve the functioning of meristematic cells, nutrient utilization efficiency, cell elongation, and promote grain development. This finding aligns with the results reported by Mehta et al*.,* (2019), Sahu et al*.,* (2022). Nano urea contains nanoscale nitrogen particles (approximately 55,000 particles) with a surface area 10,000 times greater than that of conventional 1mm urea prills. When applied as a foliar spray, these tiny particles are delivered directly into plant cells, releasing nitrogen in a controlled, phased manner according to the plant's needs. This targeted release enhances nutrient use efficiency. Upon spraying, nano urea triggers pathways for nitrogen uptake and assimilation within the plants. It improves nitrogen availability through gaseous uptake via leaf stomata and may activate various enzymes involved in biochemical pathways, contributing to the maintenance of biological membranes (Attri et al., 2022). Similarly, a field experiment by Burhan and Al-Hassan (2019) demonstrated that the application of nano fertilizers significantly increased wheat productivity. The study observed an approximate 48.9% rise in grain yield, along with substantial enhancements in various quality parameters.

3.2 Nutrient Content and Uptake

At the harvest stage of transplanted rice, the data about nutrient content (%) and uptake (kg hac-1) were displayed in Table 2 & 3 and Fig. 2 & 3, respectively. T_5: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N mixed with Nano Zn & Nano Cu had the highest content of nitrogen (%), phosphorus (%), potassium (%), copper (%), and zinc (ppm) in grain & straw. Treatment T_4: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N mixed with Nano Zn came next, and T_0 (Control) had the lowest content of nitrogen, phosphorus, potassium, copper, and zinc throughout the study. The highest uptake of nitrogen, phosphorus, potassium, copper, and zinc in grain and straw was observed under T_5: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N mixed with Nano Zn & Nano Cu. Treatment T_4: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N mixed with Nano Zn came next, and T_0 (Control) had the lowest uptake of these elements in grain and straw (kg ha^{-1}).

Nano-fertilizers enhance the surface area available for various metabolic reactions in plants. The absorption of nutrients by grain and straw was observed to be greater compared to leaves and root pore size, which may facilitate a more effective penetration of nutrients into the plant. As a result of this treatment, T_5 demonstrated a higher nutrient content and uptake in both grain and straw. Similar findings were reported by Bora et al., 2018, Javed et al. 2019, Rizwan et al.,2021 and Sahu et al., 2022. The superior performance of rice receiving two nano sprays is primarily due to the presence of nanopores and stomatal openings in the plant leaves, which facilitated the uptake of nano materials and their deeper penetration into the leaves, leading to improved nutrient use efficiency (NUE). Nano fertilizers are particularly effective because they enable efficient nutrient transport and delivery through plasmodesmata, which are nano-sized channels (50-60 nm) connecting plant cells (Attri et al., 2022; Mahanta et al., 2019).

Nanomaterials possess unique characteristics distinct from their parent materials, leading to alterations in their physicochemical properties. These changes impart exceptional traits, enhanced functionalities, and increased reactivity, primarily due to their extremely high surface-to-volume ratio (Sahoo et al., 2024; Joudeh & Linke, 2022). Their application ensures a slow and controlled release of active ingredients, addressing the issue of low fertilizer use efficiency while meeting plant nutrient demands (Sahoo et al., 2024; Tarafdar, 2020). The foliar application of nano nitrogen (N) and phosphorus (P) enables efficient nutrient management by reducing nitrogen losses to the environment and minimizing phosphorus immobilization in the soil (Sahoo et al., 2024; Mejias et al., 2021).

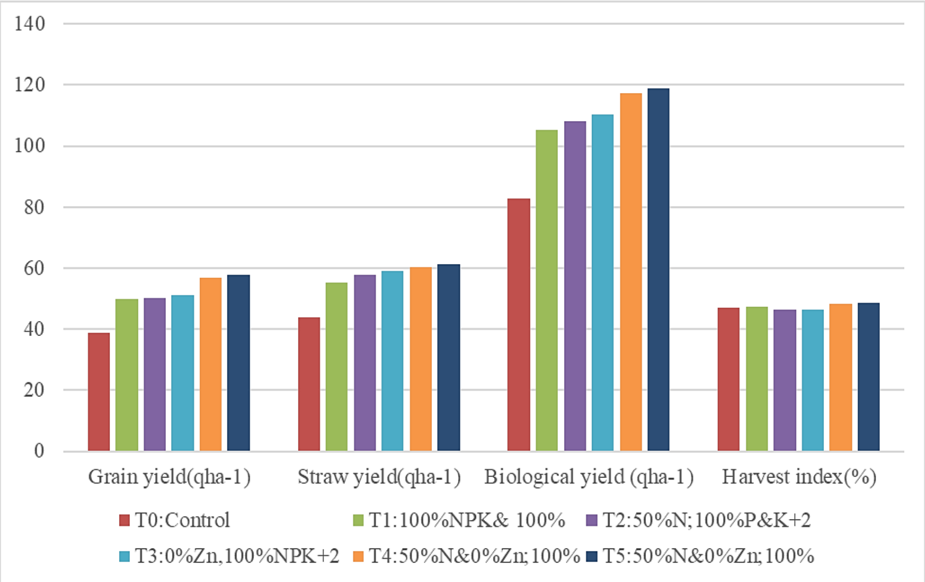

Fig. 1(A). Impact of foliar application of Nano-fertilizers on Grain yield, Straw yield, Biological yield (q ha-1) Harvest index (%) of different treatments in rice crop

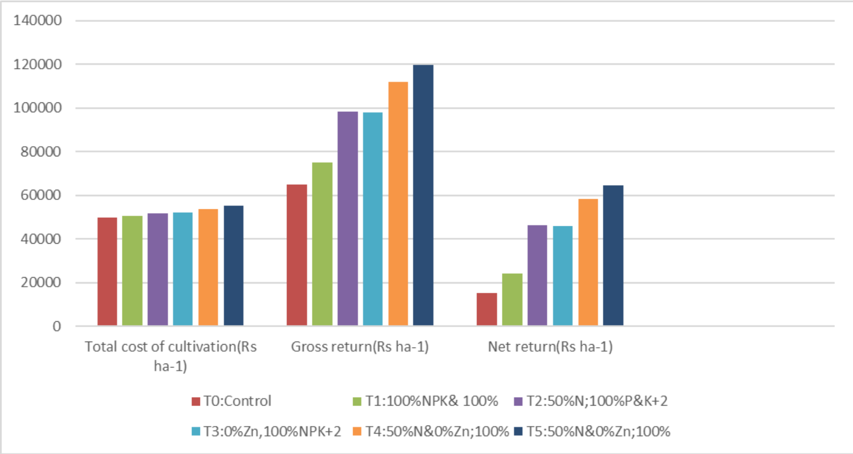

Fig.1 (B). Impact of foliar application of Nano-fertilizers on Economics of different treatments in rice crop

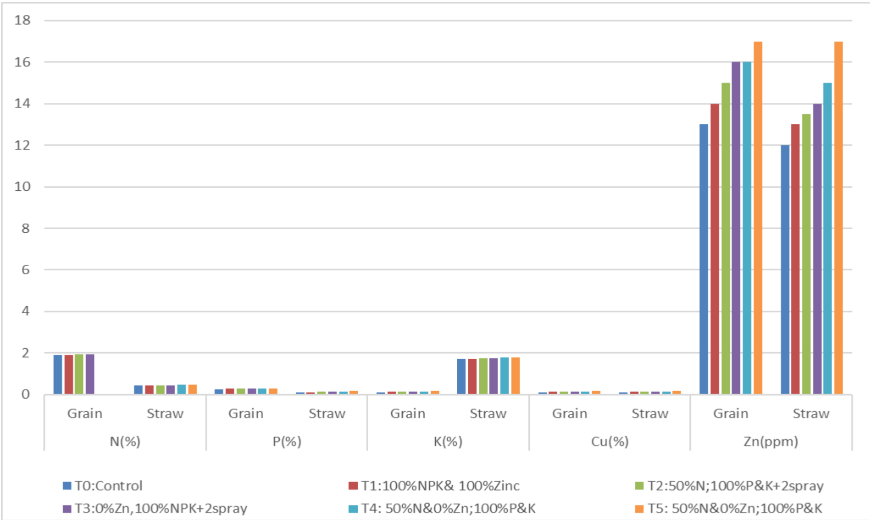

Fig. 2. Impact of foliar application of Nano-fertilizers on N (%), P (%), K (%), Cu (%) and Zn content (ppm) of different treatments in rice crop

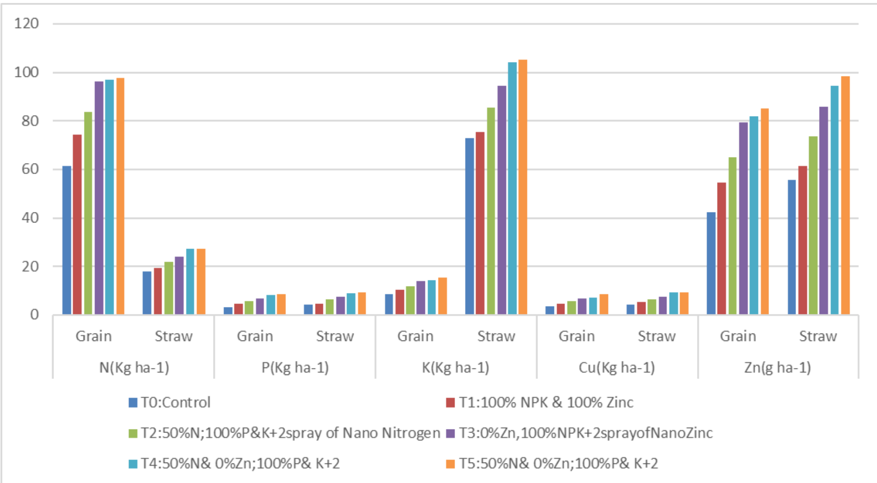

Fig. 3. Impact of foliar application of Nano-fertilizers on uptake of N (Kg ha^{-1}), P (Kg ha^{-1}), K (Kg ha^{-1}), Cu (Kg ha^{-1}) and Zn content (g ha^{-1}) different treatments in rice crop

Table 1. Impact of foliar application of Nano-fertilizers on Grain yield, Straw yield, Biological yield (q ha^{-1}), Harvest index (%) and Economics of different treatments in rice crop

Treatments	Grain Yield (q h^{1})	Straw Yield (q ha^{-1})	Biological Yield (q ha^{-1})	Harvest Index (%)	Total cost of cultivation (Rs ha^{-1})	Gross Return (Rs ha^{-1})	Net Return (Rs ha^{-1})	B:C ratio
T_0: Control	38.94	43.78	82.72	47.07	49780	65010	15230	1.30
T_1:100 % NPK & 100 % Zinc application (RDF)	49.95	55.31	105.26	47.45	50680	74967	24287	1.47
T_2:50 % N; 100 % P & K + 2 Spray of Nano Nitrogen	50.12	57.87	107.99	46.41	51780	98205	46425	1.89
T_3:0 % Zn, 100 % NPK + 2 Spray of Nano Zinc	51.28	59.07	110.35	46.47	51998	97850	45852	1.13
T_4:50 % N & 0 % Zn; 100 % P & K + 2 spray of Nano N mixed with Nano Zn	56.76	60.43	117.19	48.43	53780	112098	58318	1.08
T_5:50 % N & 0 % Zn; 100 % P & K + 2 spray of Nano N mixed with Nano Zn & Nano Cu	57.82	61.12	118.94	48.61	55130	119841	64711	2.17
SEm±	1.34	1.54	2.15	1.98	-	-	-	-
CD(P=0.05)	3.76	2.09	4.43	3.90	-	-	-	-

Table 2. Impact of foliar application of Nano-fertilizers on N (%), P (%), K (%), Cu (%) and Zn content(ppm) of different treatments in rice crop

Treatments	N (%)		P (%)		K (%)		Cu (%)		Zn (ppm)	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
T_0: Control	1.89	0.42	0.26	0.10	0.10	1.70	0.11	0.10	13	12.0
T_1:100 % NPK & 100 % Zinc Application (RDF)	1.91	0.44	0.27	0.11	0.12	1.72	0.12	0.12	14	13.0
T_2:50 % N; 100 % P & K + 2 spray of Nano Nitrogen	1.93	0.45	0.27	0.13	0.13	1.74	0.13	0.13	15	13.5
T_3:0 % Zn, 100 % NPK + 2 spray of Nano Zinc	1.94	0.45	0.28	0.14	0.14	1.76	0.14	0.14	16	14.0
T_4: 50 % N & 0 % Zn; 100 % P & K + 2 spray of Nano N mixed with Nano Zn	1.96	0.47	0.29	0.15	0.15	1.78	0.15	0.15	16	15.0
T_5: 50 % N & 0 % Zn; 100 % P & K + 2 spray of Nano N mixed with Nano Zn & Nano Cu	1.95	0.48	0.30	0.16	0.16	1.80	0.17	0.16	17	17.0
SEm±	0.32	0.38	0.046	0.35	0.031	0.22	0.025	0.07	1.25	1.18
CD(P=0.05)	NS	0.17	0.103	0.16	0.072	0.10	0.67	0.03	2.67	2.42

Table 3. Impact of foliar application of Nano-fertilizers on uptake of N (Kg ha^{-1}), P (Kg ha^{-1}), K (Kg ha^{-1}), Cu (Kg ha^{-1}) and Zn content (g ha^{-1}) different treatments in rice crop

Treatments	N (Kg ha^{-1})		P (Kg ha^{-1})		K (Kg ha^{-1})		Cu (Kg ha^{-1})		Zn (g ha^{-1})	
	Grain	**Straw**	**Grain**	**Straw**	**Grain**	**Straw**	**Grain**	**Straw**	**Grain**	**Straw**
T_0: Control	61.51	18.05	3.25	4.29	8.46	73.06	3.58	4.29	42.32	55.77
T_1:100% NPK & 100% Zinc Application (RDF)	74.37	19.26	4.67	4.81	10.51	75.30	4.67	5.25	54.51	61.29
T_2:50 % N; 100 % P & K + 2 spray of Nano Nitrogen	83.83	22.07	5.65	6.37	11.72	85.36	5.65	6.37	65.16	73.59
T_3:0 % Zn, 100 % NPK + 2 spray of Nano Zinc	96.32	24.12	6.95	7.50	13.90	94.33	6.95	7.50	79.44	85.76
T_4:50 % N & 0 % Zn; 100 % P & K + 2 Spray of Nano N mixed with Nano Zn	97.10	27.16	8.20	8.86	14.38	104.14	7.20	9.25	82.04	94.51
T_5:50 % N & 0 % Zn; 100 % P & K + 2 Spray of Nano N mixed with Nano Zn & Nano Cu	97.73	27.27	8.51	9.25	15.53	105.16	8.51	9.45	85.20	98.37
SEm±	1.09	1.32	1.02	1.00	1.12	1.69	0.58	0.63	1.71	1.83
CD(P=0.05)	2.24	1.70	2.14	2.32	2.29	3.56	1.24	1.29	3.98	3.90

3.3 Economic Feasibility

The application of T_5: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N combined with Nano Zn & Nano Cu has resulted in higher cultivation costs for transplanted rice (Rs.55,130 ha^{-1}) than all other treatments (Table 1 and Fig. 1(B). In absolute control, it was the lowest (Rs.49780 ha^{-1}). Significantly greater net returns and B:C were observed in T_5: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N combined with Nano Zn & Nano Cu (Rs. 64,711 ha^{-1} and 2.17, respectively). Nonetheless, it was discovered to be comparable to T_4: 50% N and 0% Zn; 100% P and K + 2 sprays of Nano N combined with Nano Zn (Rs. 58318 ha^{-1} and 1.08). In contrast, the control group achieved lower gross returns, net returns, and B:C (Rs. 65,010 ha^{-1}, Rs. 15,230 ha^{-1}, and 1.30). The plant produced lower yields and fetched lower returns as a result, which is why the gross returns, net returns, and B:C were lowest in the absolute control. On the other hand, traditional fertilizers applied at the base and nanofertilizers applied topically provided the necessary quantity of nutrients and led to larger yields that yielded higher returns. Rawat et al.,2017, Sangra et al., 2018 and Sankar et al., 2020 achieved similar outcomes. Attri et al. experimented to assess the effect of foliar application of nano urea on the productivity and profitability of fine rice and found positive results regarding grain yield straw yield, net return and B:C ratio. She reported that the highest number of panicles per square meter might be attributed to the adequate supply of nitrogen provided by nano urea during critical growth stages. This sustained nitrogen availability likely supported meristematic activity and stimulated cell elongation in plants, resulting in a greater number of panicles per square meter (Attri et al. 2022). These findings align closely with those reported by Jassim et al. (2019). Nutrients smaller than the stomatal pores, with a larger surface area, remain available to the plant for an extended period, contributing to increased productivity (Sahoo et al., 2024; Patil et al., 2020; Talboys et al., 2020).

4. CONCLUSION

The highest grain yield was observed in treatment T_5: 50% N & 0% Zn; 100% P & K + 2 sprays of Nano N combined with Nano Zn & Nano Cu. This yield was statistically on par with treatment T_4: 50% N and 0% Zn; 100% P and K + 2 sprays of Nano N combined with Nano Zn, and treatment T_3 : 0% Zn, 100% NPK + 2 sprays of Nano Zinc. Treatment T_5 also achieved the highest gross return (₹119,841 ha^{-1}), net return (₹64,711 ha^{-1}), and benefit-cost ratio (2.17). Furthermore, T_5 recorded the highest nitrogen (%), phosphorus (%), potassium (%), copper (%), and zinc (ppm) content in both grain and straw.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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