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Research Paper

Effect of zinc oxide nanoparticles application on growth and yield of basmati rice (*Oryza sativa*) in alkaline soil

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ABSTRACT

A field experiment was conducted during the rainy (*kharif*) seasons of 2019 and 2020 at Crop Research Centre of the Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, to study the effect of zinc oxide nanoparticles (ZnO-NPs) application on growth and yield of basmati rice (*Oryza sativa* L.) in alkaline soil. The experiment consisted of 9 treatments, replicated thrice in randomized block design using rice variety 'Pusa Basmati 1509'. The foliar application of ZnO-NPs increased the plant height by 17.9% at harvesting, number of tillers by 37.3%, dry-matter production by 15.1% and leaf-area index by 69.4% over soil application at 90 days after transplanting (DAT). Grain and straw yield also increased by 16.9% and 17.3%, respectively, compared with conventional fertilization of $ZnSO_4$. Further, the foliar application of ZnO-NPs at the panicle and flowering stage was more effective with respect to the biological yield of rice and increased by 17.0% at harvesting stage. Hence foliar application of ZnO-NPs could be preferred for Zn fertilization in rice production than conventionally soil-applied sources.

***Key words*:** Basmati rice, Growth, Yield, Zinc oxide nanoparticles

Rice (*Oryza sativa* L.) is an important crop, feeding nearly 75% of the world's population. Globally approximately, 50–80% of daily calorie is provided by rice (Elshayb *et al.,* 2021). In India, rice is the staple food to tackle the widespread malnutrition and hunger where it provides nearly 43% of the calorie requirement for more than 70% of the Indian population (Choudhary *et al.,* 2022). In rice farming, basmati holds a unique position. Basmati rice is distinguished from other aromatic rice by the fact that its length doubles from its original size after cooking. It also has other qualities including a great flavour, a superior aroma, and a distinct taste.

Zinc is crucial for numerous physiological processes that occur in flora and fauna, including the production of protein, chlorophyll, and carbohydrates (Singh *et al*., 2021). More than 300 enzyme systems utilize the mineral Zn, which is a necessary micronutrient. It is one of the most important micronutrients that affects the yield of rice. Compared to other crops, rice has a higher prevalence of zinc deficiency, with more than 50% of the crop globally susceptible to this nutritional deficiency (Ghoneim, 2016). Due to Zn immobilization by neutral to alkaline soils and poor Zn mobility in plants, soluble Zn had lower use efficiency than standard micronutrient fertilizers. Insufficiency of Zn has an impact on rice. At least 70% of the rice is grown in flooded circumstances, where increasing concentration of phosphorus and bicarbonate reduces the availability of zinc for the crop.

Nano fertilizer possessing a high surface area to volume ratio, the effectiveness of nano fertilizers may surpass the most innovative polymer-coated conventional fertilizers. One of the most crucial solutions for the rapidly growing global population is the development of zinc oxide nanoparticles (ZnO-NPs) as a possible tool for plant science. The ZnO-NPs offer promise for improving plant growth and yield (Thounaojam *et al*., 2021). Zinc oxide nanoparticles (ZnO-NPs) are an inorganic chemical that can be manufactured synthetically and come in a variety of constructed morphological forms, and solubility in water ranges from 1.6 to 5 mg/L. The ZnO nanoparticles are currently one of the most widely used metal oxides in the

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manufacturing, agricultural, and environmental sectors. Since soil-applied zinc may be converted to insoluble form owing to high *p*H, a replacement for soil-applied Zn fertilizer is required with excellent performance and low environmental risk and foliar application of Zn could be a possible option. In this regard, zinc nanoparticles may be assessed for their effectiveness. The investigation aims at assessing the effectiveness of zinc oxide nanoparticles, particularly in comparison to soil-applied zinc fertilizers for zinc nutrition in basmati rice in alkaline soil.

MATERIALS AND METHODS

The field experiment was conducted during the rainy (*kharif*) season of 2019 and 2020 at the Crop Research Centre of the Sardar Vallabhbhai Patel University of Agriculture and Technology Meerut, Uttar Pradesh. The experimental site located at 29°5'21''N, 77°41'44''E, 247 m above the mean sea-level. The soil was sandy loam, slightly alkaline, having *p*H 7.84, electrical conductivity 0.30 dS/m at 25°C and organic carbon 4.46 g/kg. The soil was low in available nitrogen (218.60 kg/ha), and medium in available phosphorus (12.80 kg/ha), potassium (243.38 kg/ha) and DTPA-extractable Zn (0.62 mg/kg). The experiment was conducted in a randomized block design with 3 replications and 9 treatments. Treatments consisted of control (no fertilizer), 100% NPK, 100% NPK + soil application of $ZnSO_4$ @ 25 kg/ha, 100% NPK + root dipping @ 100 ppm ZnO-NPs, 100% NPK + root dipping @ 100 ppm ZnO-NPs + ZnO-NPs spray at panicle initiation (35 days after transplanting) stage @ 100 ppm, 100% NPK + root dipping @ 100 ppm ZnO-NPs + ZnO-NPs spray at panicle initiation (PI) stage @ 100 ppm + ZnO-NPs spray at flowering stage @ 100 ppm, 75% NPK + root dipping @ 100 ppm ZnO-NPs, 75% NPK + root dipping @ 100 ppm ZnO-NPs + ZnO-NPs spray at PI stage @ 100 ppm, 75% NPK + root dipping @ 100 ppm ZnO-NPs + ZnO-NPs spray at PI stage @ 100 ppm + ZnO-NPs spray at flowering stage @ 100 ppm. Rice variety 'Pusa Basmati 1509' was transplanted on 10 July 2019 and 12 July 2020 during the first and second year, respectively, at a spacing of 20 cm × 15 cm with 2 seedlings/hill. Nitrogenous fertilizer was applied in 3 equal splits, i.e. 1/3rd nitrogen at the time of puddling and the remaining in 2 equal splits–at maximum tillering and panicle-initiation stage, by top-dressing. Phosphorus @ 60 kg P_2O_5/ha as diammonium phosphate and potassium @ 60 kg K_2O/ha as muriate of potash were applied at the time of transplanting. Zinc was applied as $ZnSO_4$ @ 25 kg/ha in soil and ZnO-NPs as per treatment. A foliar spray of ZnO-NPs @ 100 ppm was done at the panicle-initiation and flowering stage of rice. Five plants were tagged randomly in each net plot and their individual height was recorded in centimetres from the base to the tip of fully expanded leaves and the number of tillers were counted by using a row length of 1 m from 3 places in each plot. Five random plants from each plot were selected to record the data on yield attributes.

RESULTS AND DISCUSSION

Growth parameters

Pooled data results (Table 1) revealed that, at 60 DAT the maximum plant height (98.8 cm) found in treatment T_6 (100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage) was at par with 96.9 cm recorded with T_5 (100% NPK + root dipping ppm ZnO-NPs + ZnO-NPs spray at the PI stage) and significantly higher than the remaining treatments (Table 1). At this stage, application of nano zinc particles either with 100 or 75% NPK revealed significantly higher plant height than 100% NPK + $ZnSO_4$ soil application where a conventional source of zinc was applied through soil application.

The maximum plant height (106.6 cm) at 90 DAT was recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage and was found statistically at par with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments. The application of zinc over recommended NPK improved the plant height significantly.

Plant height declined slightly at harvesting which may be possible due to shrinkage of leaves and the maximum plant height (105.1 cm) at this stage recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found statistically at par with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments. Results showed that, application of ZnO-NPs increased the plant height by 20.8, 17.8 and 17.9% over conventional Zn application at 60 and 90 DAT, and at harvesting, respectively. The application of zinc over recommended NPK improved the plant height significantly. Plant height was significantly higher in all these treatments where zinc nano-particle was supplemented through root dipping or foliar application than 100% NPK + $ZnSO_4$ soil application. Plant height was also significantly higher in all those treatments where 25% NPK was skipped and nano zinc particles were supplemented than 100% NPK + $ZnSO_4$ soil application. The minimum plant height was recorded at 60 and 90 DAT and at harvesting were recorded in the control. These results are in harmony with those obtained by Sheteiwy *et al.,* (2021). Increase in plant height with Zn application could be owing to the concentration of tryptophan, an amino acid involved as a precursor in IAA production. The IAA (indol-3-acetic acid) is essential for cell elongation and division

Table 1. Effect of zinc oxide nanoparticles on growth parameters of basmati rice at different crop growth stages (pooled data of 2 years)

Treatment	Plant height (cm)			Tillers/m²		Leaf-area index		Dry-matter production (g/m²)	
	60 DAT	90 DAT	At harvesting	60 DAT	90 DAT	60 DAT	90 DAT	60 DAT	90 DAT
T_1, Control (no fertilizer)	64.9f	80.5f	78.6f	282.5f	328.5f	2.77f	1.44f	154.9f	370.8f
T_2, 100% NPK (120 : 60 : 60 kg/ha)	78.5e	86.4e	85.4e	313.5e	361.0e	3.54e	1.75e	396.0e	675.0e
T_3, 100% NPK + $ZnSO_4$ soil application	81.8d	90.5d	89.1d	345.5d	396.0d	4.17d	2.09d	404.5d	702.8d
T_4, 100% NPK + ZnO-NPs root dipping	88.2c	95.1c	94.0c	391.5c	447.0c	4.91c	2.56c	414.3c	751.1c
T_5, 100% NPK + ZnO-NPs root dipping + ZnO- NPs spray at PI stage	970a	101.5b	100.4b	476.5a	494.5a	6.46a	3.06b	434.6a	784.1b
T_6, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage + ZnO-NPs spray at flowering stage	98.8a	106.6a	105.1a	496.5a	543.5b	6.64a	3.54a	439.9a	808.7a
T_7, 75% NPK + ZnO-NPs root dipping	85.8c	94.0c	92.6c	380.5c	439.5c	4.76c	2.41c	411.8c	754.8c
T_8, 75% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	91.5b	98.7b	97.5b	424.5b	479.5b	5.56b	2.91b	421.9b	773.9b
T_9, 75% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage + ZnO-NPs spray at flowering stage	93.5b	105.3a	103.9a	444.0b	526.5a	5.81b	3.38a	426.0b	798.9a
CD (P=0.05)	3.15	3.56	3.13	27.03	28.76	0.58	0.55	6.52	12.77
SEm±	1.05	1.18	1.04	9.0	9.57	0.19	0.18	2.17	4.25

ZnO-NPs, Zinc oxide nanoparticles; DAT, days after transplanting; PI, panicle initiation
Values within the same column followed by different letters are significantly different at the 0.05 probability level

(Elshayb *et al.,* 2021)

The maximum tillers/m² (496.5) at 60 DAT found with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage were at par (476.5) with application of 100% NPK + root dipping ppm ZnO-NPs + ZnO-NPs spray at PI stage and significantly higher than the remaining treatments. At 90 DAT, the maximum tillers/m² (543.5) also recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage were found statistically at par (526.5) with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments. Application of zinc over recommended NPK improved the number of tillers/m² significantly. The number of tillers/m² was significantly higher in all those treatments where 25% NPK was skipped and nano zinc particles than application of 100% NPK + $ZnSO_4$ soil application @ 25 kg/ha. At 60 and 90 DAT, the minimum number of tillers/m² (282.5 and 328.5) was recorded in the control. An increase in tillers per m² might be ascribed to an adequate supply of Zn that might have increased the uptake and availability of other essential nutrients, which in turn resulted in the improvement of plant metabolic process and finally increased the number of tillers and crop growth.

The maximum dry-matter production (439.9 g/m²) at 60 DAT found with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was at par with application of 100% NPK + root dipping ppm ZnO-NPs + ZnO-NPs spray at PI stage and significantly higher than the remaining treatments. At 90 DAT in comparison to the control (370.84 g/m²), all the treatments exhibited a significant effect on dry-matter production by recording higher dry-matter accumulation. The maximum dry-matter production (808.7 g/m²) 90 DAT recorded with the application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was statistically at par (798.9 g/m²) with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments. At harvesting in comparison to the control (541.9 g/m²) all the treatments exhibited a significant effect on dry-matter production. The fertilized plot also differed significantly. Maximum dry-matter production (1212.9 g/m²) at this stage recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found statistically at par with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments. The application of zinc over recommended NPK improved the dry-matter production significantly. Foliar Zn application is easily absorbed and transported through phloem, especially in plants grown under low Zn supply and increased the growth characteristics of basmati rice.

At 60 DAT, the minimum leaf-area index (2.77) was again recorded in the control but at this stage, different treatments differed significantly. The maximum leaf-area index (6.64) recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found at par with application of 100% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and significantly higher than the remaining treatments. At 90 DAT in comparison to the control (1.44), all the treatments exhibited a significant effect on the leaf-area index. The maximum leaf-area index (3.54) at this stage recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found statistically at par (3.38) with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments.

Grain yield

The maximum grain yield (4.42 t/ha) recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found at par with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at the PI stage and flowering stage and significantly higher than the remaining treatments (Table 2). The nitrogen recommendation for basmati rice in Uttar Pradesh is 90 to 100 kg/ha. Application of zinc over recommended NPK improved the grain yield significantly. The results of the current study indicate that more dry substances could be collected if ZnO-NPs were applied through root dipping, spray at the PI and flowering stages, suggesting that ZnO-NPs would facilitate final yield increases. Notably, zinc is an essential component of hundreds of plant enzymes that participate in chlorophyll and auxin synthesis and the synthesis and transformation of carbohydrates. Increased levels of zinc in rice will promote photosynthesis and photosynthetic efficiency. High production of photosynthetic substances is essential to achieve a high grain yield (Zhang *et al.,* 2021). Improved nutrient intake in conjunction with Zn fertilization may increase the number of panicles/panicle, as well as photosynthetic output, leading to an increase in rice yield (Nandy *et al.,* 2022). Similar findings were reported by Ghasal *et al.,* (2015) and Bana *et al.,* (2022).

Straw yield

Maximum straw yield (5.43 t/ha) obtained with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found statistically at par with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage and significantly higher than the remaining treatments (Table 2). The application of zinc over recommended NPK improved the straw yield significantly. The straw yield was also significantly higher in all these treatments where 25% NPK was skipped and nano zinc particles were applied than application of 100% NPK + $ZnSO_4$ soil application @ 25 kg/ha. In comparison to the control (3.01 t/ha), all the treatments exhibited a significant effect on straw yield. Our results confirm the finding of Sheykhbaglou *et al.,* (2018) and Nandy *et al.,* (2022).

Biological yield

The maximum biological yield (9.85 t/ha) recorded with application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage was found statistically

Table 2. Effect of zinc oxide nanoparticles on yields of basmati rice (pooled data of 2 years)

Treatment	Biological yield (t/ha)	Grain yield (t/ha)	Straw yield (t/ha)
T_1, Control (no fertilizer)	5.11f	2.10f	3.01f
T_2, 100% NPK (120 : 60 : 60 kg/ha)	7.79e	3.33e	4.46e
T_3, 100% NPK + $ZnSO_4$ soil application	8.42d	3.78d	4.63d
T_4, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	8.85c	4.00c	4.86c
T_5, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	9.32b	4.19b	5.13b
T_6, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage + ZnO-NPs spray at flowering stage	9.85a	4.42a	5.43a
T_7, 75% NPK + ZnO-NPs root dipping	8.79c	3.93c	4.86c
T_8, 75% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	9.17b	4.14b	5.03b
T_9, 75% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage + ZnO-NPs spray at flowering stage	9.73a	4.33a	5.40a
CD (P=0.05)	0.23	0.13	0.16
SEm±	0.08	0.04	0.05

ZnO-NPs, Zinc oxide nanoparticles; PI, panicle initiation

Values within the same column followed by different letters are significantly different at the 0.05 probability level at par with application of 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage (9.73 t/ha) and significantly higher than the remaining treatments (Table 2). The application of zinc over recommended NPK improved the biological yield significantly. The biological yield was significantly higher in all these treatments where zinc nano-particles were supplemented through root dipping or foliar application than the application of 100% NPK + $ZnSO_4$ soil application @ 25 kg/ha. In comparison to all the treatments, the lowest biological yield (5.11 t/ha) was found in the control. Similar findings were reported by Bana *et al.,* (2022).

Enhanced enzymatic activity with zinc application led to an effectively increased rate of photosynthesis, transfer of photo-assimilates to the grain and increase in panicle weight, number of filled grains, and 1,000-grain weight (Elshayb *et al.,* 2021).

Nutrient uptake

Nutrients uptake varied with the treatments and highest nitrogen, phosphorus, potassium and zinc uptake were recorded with the application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage (T_6), while the lowest in control (Table 3). The treatment T_6 with the highest total N uptake (102.95 kg/ha) was statistically at par with T_9 where 75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage was applied. Similarly, phosphorus (25.73 kg/ha), potassium (106.23 kg/ha) and zinc uptake (394.18 g/ha) recorded highest in treatment T_6 (100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage) was at par with T_9 (75% NPK + root dipping ZnO-NPs + ZnO-NPs spray at PI stage and flowering stage). It was clearly observed that application of nano zinc particles with either 100% or 75% NPK resulted in significantly higher nutrients uptake as compared to conventional zinc application in soil. Similar findings were also reported by Bana *et al.,* (2022) in basmati rice.

Economics

The application of ZnO-NPs was found economically superior to conventional zinc sulphate application in soil in terms of gross return, net return and benefit: cost ratio (Table 3). Treatment 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage, resulted in the highest gross and net returns (90,998 ₹/ha and 41,563 ₹/ha, respectively). The application of 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage resulted in a 34.27% increase in net returns compared with conventional soil application of zinc. Treatment T_6 having 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage provided an additional return of 10,608 ₹/ha as compared to soil application of zinc sulphate. The benefit: cost ratio, was the highest in treatment 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI and flowering stage with ratios of 1.84. These results confirm the finding of Nandy *et al.,* (2022).

Based on a 2-years field study, it can be concluded that the application of zinc oxide nanoparticles in addition to recommended NPK fertilizers significantly improved

Table 3. Effect of zinc oxide nanoparticles on nutrient uptake and economics of basmati rice (pooled data of 2 years)

Treatment	Total N uptake (kg/ha)	Total P uptake (kg/ha)	Total K uptake (kg/ha)	Total Zn uptake (g/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	Benefit: cost ratio
T_1, Control (no fertilizer)	33.56f	4.83f	44.06f	111.43f	44,208f	19,64h	1.05e
T_2, 100% NPK (120 : 60 : 60 kg/ha)	56.63e	10.01e	69.71e	224.41e	69,388e	23,184g	1.5d
T_3, 100% NPK + $ZnSO_4$ soil application	67.72d	13.35d	76.52d	276.88d	77,959d	30,955f	1.66c
T_4, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	79.11c	17.22c	85.19c	309.29c	82,220c	35,135de	1.75b
T_5, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	89.97b	21.24b	95.21b	349.94b	86,222b	37,963bc	1.79ab
T_6, 100% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage + ZnO-NPs spray at flowering stage	102.95a	25.73a	106.23a	394.18a	90,998a	41,563a	1.84a
T_7, 75% NPK + ZnO-NPs root dipping	76.17c	16.28c	83.94c	299.3c	81,118c	34,686e	1.75b
T_8, 75% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage	87.35b	20.3b	92.46b	339.97b	85,142b	37,535cd	1.79ab
T_9, 75% NPK + ZnO-NPs root dipping + ZnO-NPs spray at PI stage + ZnO-NPs spray at flowering stage	98.88a	24.73a	103.87a	380.81a	89,395a	40,613ab	1.83a
CD (P=0.05)	5.58	1.99	5.70	22.36	2,695.26	2,695.63	0.06
SEm±	1.85	0.66	1.88	7.40	891.35	891.47	0.02

ZnO-NPs, Zinc oxide nanoparticles; PI, panicle initiation
Values within the same column followed by different letters are significantly different at the 0.05 probability level

growth, yield, nutrient uptake, and economic outcomes in basmati rice. Treatments where zinc nanoparticles were supplemented through root dipping or foliar application showed higher growth and yield than conventional zinc application through soil. Notably, significant improvements were observed in treatments where 25% of NPK fertilizer was skipped and nano zinc particles were used.

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