



RESEARCH ARTICLE

Nano zinc mediated modulation of growth, yield and nutrient partitioning in kharif rice (*Oryza sativa* L.)

Boddu Archana¹, Bindhu J S^{2*}, Shalini Pillai P¹, Jacob John², Meera A V¹ & Pratheesh P Gopinath²

¹Department of Agronomy, College of Agriculture, Kerala Agricultural University, Vellayani, Thiruvananthapuram 695 522, Kerala, India

²Integrated Farming System Research Station, Kerala Agricultural University, Karamana, Thiruvananthapuram 695 002, Kerala, India

*Correspondence email - bindu.js@kau.in

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Abstract

Zinc (Zn) deficiency, aggravated by high phosphorus availability, is a major constraint to rice productivity in intensive cropping systems. A field experiment was conducted during the kharif (2022–23) in Kerala, India, to evaluate the effect of nano zinc nutrition on growth, yield formation and macronutrient uptake in rice (*Oryza sativa* L.). The experiment was laid out in a randomized block design (RBD) with 8 treatments and 3 replications. The plot size was 6 × 4.5 m with a spacing of 20 × 15 cm. The treatments were: T₁ - soil application of zinc sulphate (ZnSO₄) at 20 kg ha⁻¹, T₂ - nutri priming (NP) with nano Zn at 0.05 %, T₃ - NP with nano Zn at 0.05 % + foliar spray (FS) with nano Zn at 0.05 % at maximum tillering (MT) stage, T₄ - NP with ZnSO₄ at 0.5 %, T₅ - NP with ZnSO₄ at 0.5 % + FS with nano Zn at 0.05 % at MT stage, T₆ - FS with Nano Zn at 0.05 % at MT stage and panicle initiation (PI) stage, T₇ - FS with ZnSO₄ at 0.5 % at MT stage and PI stage, T₈ - control (recommended dose of nutrients without application of phosphorous (P) and Zn). Nutri priming with Nano Zn at 0.05 % + FS with nano Zn at 0.05 % at MT stage (T₃) resulted in taller plants with higher number of productive tillers. Grain yield was significantly influenced by the treatments and increased by 78.14 % in T₃ and 68.72 % in T₆ compared to control. Yield enhancement was associated with higher nitrogen (N), P and potassium (K) uptake at both panicle initiation (PI) and harvest under nano Zn treatments. The study revealed that nano Zn nutrition, especially through NP and stage-specific foliar application, effectively enhanced nutrient use efficiency and rice productivity in high phosphorus soils.

Keywords: maximum tillering; nano zinc; nutri priming; panicle initiation; zinc sulphate

Introduction

Rice (*Oryza sativa* L.) is a major cereal crop sustaining more than half of the global population, with Asia contributing over 90 % of world production. In India, rice occupies nearly 51.4 million hectares with a production of 179 million tonnes, making it central to national food security and farm livelihoods (1). The productivity of rice-based systems, particularly during the kharif season, depends largely on efficient nutrient management under intensive cultivation practices.

Among micronutrients, zinc (Zn) plays a pivotal role in determining growth, productivity and nutrient dynamics in rice as it is an essential component of several enzymatic and metabolic processes, including photosynthesis, protein synthesis, membrane integrity and hormone regulation (2). Adequate Zn supply enhances chlorophyll formation, promotes tillering, improves root growth and facilitates efficient translocation of nutrients within the plant. Conversely, Zn deficiency leads to impaired growth, reduced nutrient uptake and significant yield losses in rice (3).

The widespread occurrence of Zn deficiency in Indian soils, particularly under submerged rice ecosystems, poses a major constraint to achieving higher productivity. This problem is further intensified in soils receiving high phosphorus inputs, where antagonistic interactions between phosphorous (P) and Zn reduce Zn availability to plants (4). Under such conditions, inadequate Zn

supply not only restricts biomass accumulation and grain yield but also lowers nutrient use efficiency and grain nutritional quality(5).

Supplying Zn through appropriate fertilisation strategies has been shown to significantly improve nutrient uptake and yield in rice. Zinc application enhances the absorption and utilisation of both macro- and micronutrients by improving root development and enzymatic activity, thereby increasing nutrient use efficiency (6). Improved Zn nutrition also contributes to higher grain yield and better partitioning of nutrients between vegetative and reproductive plant parts, ultimately translating into greater economic returns (7).

However, the efficiency of conventional Zn fertilisers is often limited by soil fixation, leaching losses and low recovery by crops (8). In this context, advanced Zn delivery systems such as nano Zn fertilisers offer a promising approach for improving Zn availability and uptake efficiency. Due to their small particle size and higher reactivity, nano Zn formulations facilitate better absorption and translocation, enabling enhanced nutrient use efficiency at lower application rates (4). Nano Zn with 10000 ppm was used for the study. Therefore, optimising zinc supply, particularly through efficient Zn sources, is critical for enhancing growth, nutrient uptake, yield, nutrient use efficiency and overall profitability of kharif rice. Understanding the response of rice to improved Zn nutrition will provide valuable insights for developing sustainable and economically viable nutrient management strategies in rice-based cropping systems.

Materials and Methods

A field experiment was conducted during the kharif season of 2022–23 (April–August) at the Integrated Farming System Research Station, Karamana, Thiruvananthapuram, Kerala, India. The experimental site is located at 8°28'26" N latitude and 76°57'38" E longitude, at an altitude of 10 m above mean sea level. The soil of the experimental field was sandy clay loam, acidic in reaction (pH - 5.15), normal in electrical conductivity (0.78 dS m⁻¹), high in organic carbon (1.64 %), medium in available nitrogen (N) (365.79 kg ha⁻¹), high in available phosphorus (P) (27.2 kg ha⁻¹) and low in available potassium (K) (56 kg ha⁻¹). The field had been previously cultivated with transplanted rice.

The experiment experienced a humid climate with frequent rainfall during the cropping period. The crop duration was 140 days and the total rainfall received during the season was 540.01 mm. The rice variety Uma (MO-16), a medium-duration variety released by the Rice Research Station, Moncompu, Kerala Agricultural University, was used for the study.

The experiment was laid out in a randomized block design (RBD) with 8 treatments and 3 replications. The treatments were: T₁ - soil application of zinc sulphate (ZnSO₄) at 20 kg ha⁻¹, T₂ - nutri priming (NP) with nano Zn at 0.05 %, T₃ - NP with nano Zn at 0.05 % + foliar spray (FS) with nano Zn at 0.05 % at maximum tillering (MT) stage, T₄ - NP with ZnSO₄ at 0.5 %, T₅ - NP with ZnSO₄ at 0.5 % + FS with nano Zn at 0.05 % at MT stage, T₆ - FS with nano Zn at 0.05 % at MT stage and PI stage, T₇ - FS with ZnSO₄ at 0.5 % at MT stage and PI stage, T₈ - control (Recommended dose of nutrients without application of P and Zn).

Seedlings were raised in a wet nursery and transplanted to the main field 21 days after sowing. A seed rate of 75 kg ha⁻¹ was followed. In NP treatments, seeds were soaked in the respective nutrient solutions (nano Zn at 0.05 % and ZnSO₄ at 0.5 %) for 16 hr before sowing.

Lime was applied at 600 kg ha⁻¹ in two splits, with half applied as basal and the remaining half at 30 days after transplanting. Fertilisers were applied based on soil test-based recommendations as per the package of practices, Kerala Agricultural University, supplying 63.9 kg N ha⁻¹, 21.6 kg P ha⁻¹ and 87.75 kg K ha⁻¹.

The height was measured from the base of the plant to the tip of the longest leaf at flowering and at harvest. Measurements were taken from the base of the plant to the tip of the longest leaf or the panicle, whichever was longer and the mean plant height was expressed in centimeters (cm). The number of tillers was recorded from tagged sample hills at flowering and harvest stages. Tiller counts were converted to as per square meter basis and the mean value was expressed as tillers m⁻². The leaf area index (LAI) was determined at the panicle initiation (PI) stage. Leaf area was measured from six representative sample hills and expressed as the ratio of total leaf area to the corresponding ground area occupied by the sampled hills. The LAI was calculated using the following formula:

$$LAI = \frac{\text{Total leaf area of six sample hills (cm}^2\text{)}}{\text{Land area occupied by six sample hills (cm}^2\text{)}}$$

At harvest, the number of productive tillers was recorded from six randomly selected hills within the net plot area and expressed as productive tillers hill⁻¹.

The number of grains per panicle was determined by counting the spikelets from ten randomly selected panicles in each plot. The sterility percentage was calculated using the following formula:

Sterility percentage =

$$\frac{\text{Number of unfilled grains per panicle}}{\text{Number of total grains per panicle}} \times 100 \quad (\text{Eqn. 1})$$

The thousand-grain weight was determined by counting 1000 fully filled grains from the cleaned and sun-dried produce of each net plot and the weight was recorded in grams (g).

Dry matter production was estimated at harvest through destructive sampling. Six hills were randomly selected from the designated sampling area outside the net plot, excluding border rows. The plant samples were washed to remove adhering soil, air-dried for two days and subsequently oven-dried at 65 ± 5 °C until a constant weight was achieved. Dry matter accumulation was expressed as g hill⁻¹.

The harvest index (HI) was expressed as the ratio of economic yield to biological yield using the following formula (9):

$$HI = \text{Economic yield/Biological yield} \quad (\text{Eqn.2})$$

Plant samples were collected at the panicle initiation stage and harvest for nutrient uptake analysis. The samples were washed to remove adhering soil, air-dried for two days and oven dried at 65 ± 5 °C to constant weight, ground and stored for analysis. A known quantity of the dried plant material was accurately weighed and subjected to appropriate acid digestion or extraction for nutrient estimation. At panicle initiation, nutrient uptake was determined separately for roots and shoots, while at harvest, uptake was estimated separately for roots, shoots and grains. Nitrogen was analysed by the micro-Kjeldahl method after digestion with concentrated sulphuric acid, phosphorus by nitric-perchloric acid (9 : 4) digestion followed by spectrophotometric determination using the vanado-molybdate yellow colour method and P by nitric-perchloric acid digestion using flame photometry (10). Calcium (Ca) was estimated using atomic absorption spectrophotometry after nitric-perchloric acid digestion (11), zinc and iron (Fe) by atomic absorption spectrophotometry following nitric-perchloric acid digestion (12) and boron (B) by hot water extraction and spectrophotometric estimation using the Azomethine-H method (13). Nutrient uptake was calculated by multiplying nutrient concentration with the corresponding dry matter yield.

Results

Effect of Zn treatments on rice growth plant height varied significantly among treatments at both flowering and harvest stages during the kharif season (Table 1). Across both stages, T₃ consistently recorded the highest plant height, measuring 112.45 cm at flowering and 124.87 cm at harvest and remained statistically comparable with T₂ (108.33 and 116.53 cm, respectively) and T₆ (106.39 and 113.15 cm, respectively). In contrast, T₈ consistently recorded the lowest plant height at both stages (63.37 cm at flowering and 72.81 cm at harvest) and was on par with T₁ (75.50 and 81.90 cm) and T₄ (79.10 and 86.90 cm).

The number of tillers m⁻² differed significantly among treatments at the flowering and harvest stages during the kharif season (Table 1). At flowering, the maximum tiller density was

Table 1. Growth parameters of rice as affected by the varied zinc nutrition

Treatments		Plant height		Tillers m ⁻²		Panicle initiation
		Flowering	At harvest	Flowering	At harvest	LAI
T ₁	SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in kharif season)	75.50 ± 4.68 ^{cd}	81.90 ± 7.59 ^{cd}	476 ± 96 ^{cd}	389 ± 17 ^{cd}	2.35 ± 0.11 ^d
T ₂	NP with Nano Zn at 0.05 %	108.33 ± 10.92 ^{ab}	116.53 ± 11.06 ^{ab}	623 ± 115 ^{ab}	573 ± 96 ^{ab}	3.31 ± 0.45 ^{ab}
T ₃	NP with Nano Zn at 0.05 % + FS with Nano Zn at 0.05 % at MT stage	112.45 ± 26.40 ^a	124.87 ± 20.35 ^a	677 ± 45 ^a	658 ± 61 ^a	3.67 ± 0.63 ^a
T ₄	NP with ZnSO ₄ at 0.5 %	79.10 ± 4.98 ^{cd}	86.90 ± 8.64 ^{cd}	455 ± 82 ^{cd}	413 ± 54 ^{cd}	2.24 ± 0.17 ^d
T ₅	NP with ZnSO ₄ at 0.5 % + FS with Nano Zn at 0.05 % at MT stage	89.94 ± 7.01 ^{bc}	100.84 ± 8.35 ^{bc}	534 ± 85 ^{bc}	509 ± 82 ^{bc}	3.00 ± 0.20 ^{bc}
T ₆	FS with Nano Zn at 0.05 % at MT and PI stages	106.39 ± 9.68 ^{ab}	113.15 ± 13.44 ^{ab}	650 ± 28 ^{ab}	571 ± 114 ^{ab}	3.15 ± 0.41 ^{abc}
T ₇	FS with ZnSO ₄ at 0.5 % at MT and PI stages	88.56 ± 2.13 ^{bc}	98.63 ± 10.74 ^{bc}	545 ± 71 ^{bc}	495 ± 65 ^{bcd}	2.66 ± 0.23 ^{cd}
T ₈	Control (RDN without application of P and Zn)	63.37 ± 7.04 ^d	72.81 ± 7.85 ^d	411 ± 84 ^d	357 ± 112 ^d	2.31 ± 0.25 ^d
	SEm (±)	6.57	7.2	39	48	0.21
	CD (0.05)	19.939	21.839	119	148	0.636

NP: nano priming; FS: foliar spray; MT: maximum tillering; PI: panicle initiation; LAI: leaf area index; RDN: recommended dose of nitrogen; ZnSO₄: zinc sulphate.

recorded in T₃ (677 tillers m⁻²), which was statistically on par with T₆ (650 tillers m⁻²) and T₂ (623 tillers m⁻²). The lowest tiller number at flowering was observed in T₈ (411 tillers m⁻²) and was on par with T₁ (476 tillers m⁻²) and T₄ (455 tillers m⁻²). Similarly, at harvest, T₃ (658 tillers m⁻²) consistently recorded the highest tiller density and remained on par with T₂ (573 tillers m⁻²) and T₆ (571 tillers m⁻²). The minimum tiller number at harvest was recorded in T₈ (357 tillers m⁻²), which was statistically comparable with T₁ (389 tillers m⁻²) and T₄ (413 tillers m⁻²).

At PI stage the highest LAI was recorded in T₃ (3.67) (Table 1), which was on par with T₂ (3.31) and T₆ (3.15). The lowest LAI was observed in T₄ (2.24), T₈ (2.31) and T₁ (2.35) which were comparable to T₇ (2.66).

Yield attributes and dry matter production were significantly influenced by the treatments (Table 2). The highest number of productive tillers hill⁻¹ was recorded in T₃ (14), which was statistically on par with T₆ and T₂ (15), while the lowest value occurred in T₈ (16) and remained on par with T₁ (10). Dry matter production at harvest followed a similar trend, with T₃ (37.38 g hill⁻¹) registering the maximum accumulation, statistically comparable with

T₆ (35.36 g hill⁻¹), whereas the minimum dry matter production was observed in T₈ (20.13 g hill⁻¹) and was on par with T₁ (23.41 g hill⁻¹). Sterility percentage varied significantly among treatments, with the lowest sterility recorded in T₃ (6.51 %), which was on par with T₆ (7.00 %), while the highest sterility was observed in the control T₈ (16.59 %). Similarly, the number of grains per panicle was significantly higher in T₃ (217), remaining on par with T₆ (210) and T₂ (190), whereas the lowest grain number was recorded in T₈ (136), which was comparable with T₁ and on par with T₄ (149).

Grain and straw yields were significantly influenced by the treatments (Table 3). The highest grain yield was recorded in T₃ (5025 kg ha⁻¹), which was statistically on par with T₆ (4753 kg ha⁻¹) and T₂ (4494 kg ha⁻¹), while the lowest grain yield was observed in the control T₈ (2988 kg ha⁻¹) and remained on par with T₁ (3222 kg ha⁻¹) and T₄ (3272 kg ha⁻¹). A similar trend was observed for straw yield, with T₃ recording the maximum straw yield (5864 kg ha⁻¹), which was statistically comparable with T₆ (5432 kg ha⁻¹) and T₂ (5383 kg ha⁻¹), whereas the minimum straw yield was recorded in T₈ (3519 kg ha⁻¹) and was on par with T₁ (3889 kg ha⁻¹) and T₄ (4074 kg ha⁻¹).

Table 2. Effect of the zinc nutrition on the yield parameters of the rice

Treatments		Productive tillers per hill	Dry matter production at harvest (g per hill)	Sterility (%)	No. grains per panicle	Thousand grain weight (g)
T ₁	SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in kharif season)	11 ± 1 ^{cd}	23.41 ± 1.32 ^{ef}	15.20 ± 1.07 ^{ab}	138 ± 15 ^d	23.48 ± 2.69
T ₂	NP with Nano Zn at 0.05 %	17 ± 1 ^{ab}	31.80 ± 4.17 ^{bc}	9.08 ± 0.60 ^{cd}	190 ± 10 ^{ab}	25.18 ± 1.95
T ₃	NP with Nano Zn at 0.05 % + FS with Nano Zn at 0.05 % at MT stage	19 ± 4 ^a	37.38 ± 3.97 ^a	6.51 ± 0.84 ^e	217 ± 16 ^a	26.33 ± 1.61
T ₄	NP with ZnSO ₄ at 0.5 %	12 ± 1 ^{cd}	25.81 ± 4.48 ^{de}	13.81 ± 0.93 ^b	149 ± 8 ^{cd}	24.58 ± 1.94
T ₅	NP with ZnSO ₄ at 0.5 % + FS with Nano Zn at 0.05 % at MT stage	16 ± 1 ^b	31.50 ± 5.94 ^{bc}	9.85 ± 1.53 ^c	183 ± 35 ^b	26.20 ± 1.86
T ₆	FS with Nano Zn at 0.05 % at MT and PI stages	17 ± 4 ^{ab}	35.36 ± 2.36 ^{ab}	7.00 ± 0.87 ^{de}	210 ± 40 ^{ab}	26.65 ± 1.53
T ₇	FS with ZnSO ₄ at 0.5 % at MT and PI stages	14 ± 2 ^{bc}	29.72 ± 3.71 ^{cd}	10.81 ± 1.37 ^c	179 ± 9 ^{bc}	24.49 ± 3.77
T ₈	Control (RDN without application of P and Zn)	9 ± 1 ^d	20.13 ± 3.52 ^f	16.59 ± 2.31 ^a	136 ± 4 ^d	23.87 ± 2.58
	SEm (±)	1	1.79	0.69	10	1.22
	CD (0.05)	3	5.441	2.088	32	NS

NP: nano priming; FS: foliar spray; MT: maximum tillering; PI: panicle initiation; RDN: recommended dose of nitrogen; ZnSO₄: zinc sulphate; NS: non-significant.

Table 3. Effect of the zinc nutrition on grain yield, straw yield and harvest index of the rice

Treatments	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	HI
T ₁ SA of ZnSO ₄ at 20 kg ha ⁻¹ (applied only in kharif season)	3222 ± 74 ^{ef}	3889 ± 490 ^{de}	0.45 ± 0.04
T ₂ NP with Nano Zn at 0.05 %	4494 ± 406 ^{abc}	5383 ± 299 ^{ab}	0.45 ± 0.04
T ₃ NP with Nano Zn at 0.05 % + FS with Nano Zn at 0.05 % at MT stage	5025 ± 817 ^a	5864 ± 315 ^a	0.46 ± 0.05
T ₄ NP with ZnSO ₄ at 0.5 %	3272 ± 107 ^{def}	4074 ± 926 ^{cde}	0.45 ± 0.06
T ₅ NP with ZnSO ₄ at 0.5 % + FS with Nano Zn at 0.05 % at MT stage	4049 ± 223 ^{bcd}	5000 ± 556 ^{abc}	0.45 ± 0.04
T ₆ FS with Nano Zn at 0.05 % at MT and PI stages	4753 ± 822 ^{ab}	5432 ± 214 ^{ab}	0.46 ± 0.03
T ₇ FS with ZnSO ₄ at 0.5 % at MT and PI stages	3802 ± 344 ^{cde}	4506 ± 466 ^{bcd}	0.46 ± 0.05
T ₈ Control (RDN without application of P and Zn)	2988 ± 43 ^f	3519 ± 490 ^e	0.46 ± 0.03
SEm (±)	257	312	0.03
CD (0.05)	781	947	NS

NP: nano priming; FS: foliar spray; MT: maximum tillering; PI: panicle initiation; HI: harvest index; RDN: recommended dose of nitrogen; ZnSO₄: zinc sulphate; NS: non-significant.

Nutrient uptake

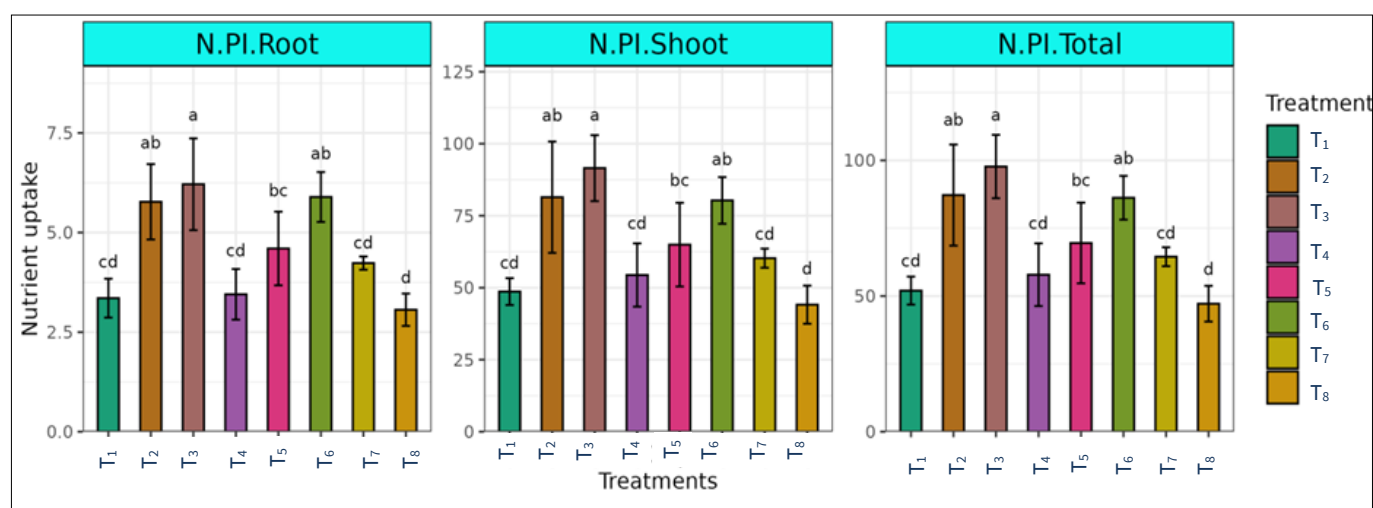
Panicle initiation stage

Macronutrient uptake by rice differed significantly among the treatments during the kharif season at the PI stage. Root N uptake (Fig. 1) was highest in T₃ (6.21 kg ha⁻¹), on par with T₂ (5.77 kg ha⁻¹) and T₆ (5.89 kg ha⁻¹), whereas the lowest uptake was recorded in T₈ (3.06 kg ha⁻¹), on par with T₁ (3.35 kg ha⁻¹), T₄ (3.45 kg ha⁻¹) and T₇ (4.23 kg ha⁻¹). Shoot N uptake (Fig. 1) was highest in T₃ (91.52 kg ha⁻¹), on par with T₂ (81.43 kg ha⁻¹) and T₆ (80.31 kg ha⁻¹), while the lowest uptake occurred in T₈ (44.11 kg ha⁻¹), on par with T₁ (48.65 kg ha⁻¹) and T₄ (54.41 kg ha⁻¹). Consequently, total N uptake was highest in T₃ (97.73 kg ha⁻¹), on par with T₂ (87.21 kg ha⁻¹) and T₆ (86.20 kg ha⁻¹). Root P uptake (Fig. 2) was the highest in T₃ (1.50 kg ha⁻¹), on par with T₆ (1.31 kg ha⁻¹), whereas the lowest uptake was recorded in T₈ (0.55 kg ha⁻¹), T₁ (0.61 kg ha⁻¹) and T₄ (0.70 kg ha⁻¹). Shoot P uptake (Fig. 2) was highest in T₃ (12.42 kg ha⁻¹), on par with T₆ (11.16 kg ha⁻¹), while the lowest uptake occurred in T₈ (5.36 kg ha⁻¹), on par with T₁ and T₄. Root potassium (K) uptake (Fig. 3) was highest in T₃ (4.65 kg ha⁻¹), whereas the lowest uptake was recorded in T₈ (2.61 kg ha⁻¹), T₁ (2.80 kg ha⁻¹) and T₄ (2.76 kg ha⁻¹). Shoot and total K uptake (Fig. 3) were highest in T₃ (79.23 and 83.88 kg ha⁻¹, respectively), on par with T₂ (75.13 and 79.50 kg ha⁻¹) and T₆ (72.91 and 77.40 kg ha⁻¹), while the lowest uptake was observed in T₈ (45.84 and 48.45 kg ha⁻¹), on par with T₁ (50.03 and 52.83 kg ha⁻¹) and T₄ (55.27 and 58.03 kg ha⁻¹).

Harvest stage

At harvest, a similar trend was observed for macronutrient uptake across treatments. Root N uptake (Fig. 4) was highest in T₃ (4.95 kg ha⁻¹), on par with T₆ (4.46 kg ha⁻¹) and T₂ (4.38 kg ha⁻¹), while the lowest uptake (Fig. 4) was recorded in T₈ (2.03 kg ha⁻¹), T₁ (2.28 kg ha⁻¹) and T₄ (2.44 kg ha⁻¹). Shoot and grain N uptake were also highest in T₃ (55.74 and 61.26 kg ha⁻¹, respectively), on par with T₆ (52.65 and 54.98 kg ha⁻¹), whereas the lowest uptake occurred in T₈ (26.65 and 28.68 kg ha⁻¹), on par with T₁ (30.28 and 33.16 kg ha⁻¹) and T₄ (31.61 and 34.39 kg ha⁻¹). Consequently, total N uptake (Fig. 4) at harvest was highest in T₃ (121.94 kg ha⁻¹), on par with T₆ (112.08 kg ha⁻¹), while the lowest uptake was recorded in T₈ (57.36 kg ha⁻¹), T₁ (65.72 kg ha⁻¹) and T₄ (68.44 kg ha⁻¹). Potassium uptake (Fig. 5) at harvest followed a similar pattern, with the highest root, shoot, grain and total K uptake in T₃ (2.44, 32.21, 16.62 and 74.50 kg ha⁻¹, respectively), on par with T₆ (2.28, 35.68, 14.95 and 69.35 kg ha⁻¹) and T₂ (2.22 and 66.39 kg ha⁻¹ for root and total), whereas the lowest uptake (Fig. 5) was recorded in T₈ (1.22, 32.21, 7.44 and 40.87 kg ha⁻¹), on par with T₁ (1.29, 35.68, 8.03 and 45.00 kg ha⁻¹) and T₄ (1.32, 37.47, 9.09 and 47.88 kg ha⁻¹).

A comparable treatment response was evident for P uptake, wherein root P uptake (Fig. 6) was highest in T₃ (1.50 kg ha⁻¹), on par with T₆ (1.31 kg ha⁻¹), while the lowest uptake occurred in T₈ (0.55 kg ha⁻¹), T₁ (0.61 kg ha⁻¹) and T₄ (0.70 kg ha⁻¹). Shoot and grain P uptake (Fig. 6) were also maximised in T₃ (12.42 and 13.49 kg ha⁻¹), remaining on par with T₆ (11.16 and 13.28 kg ha⁻¹) and T₂ (13.13 kg ha⁻¹ for grain), resulting in the highest total P uptake in T₃ (27.41 kg ha⁻¹), with the lowest total uptake consistently recorded in T₈, T₁ and T₄.

**Fig. 1.** Root, shoot and total nitrogen uptake at panicle initiation stage in kharif.

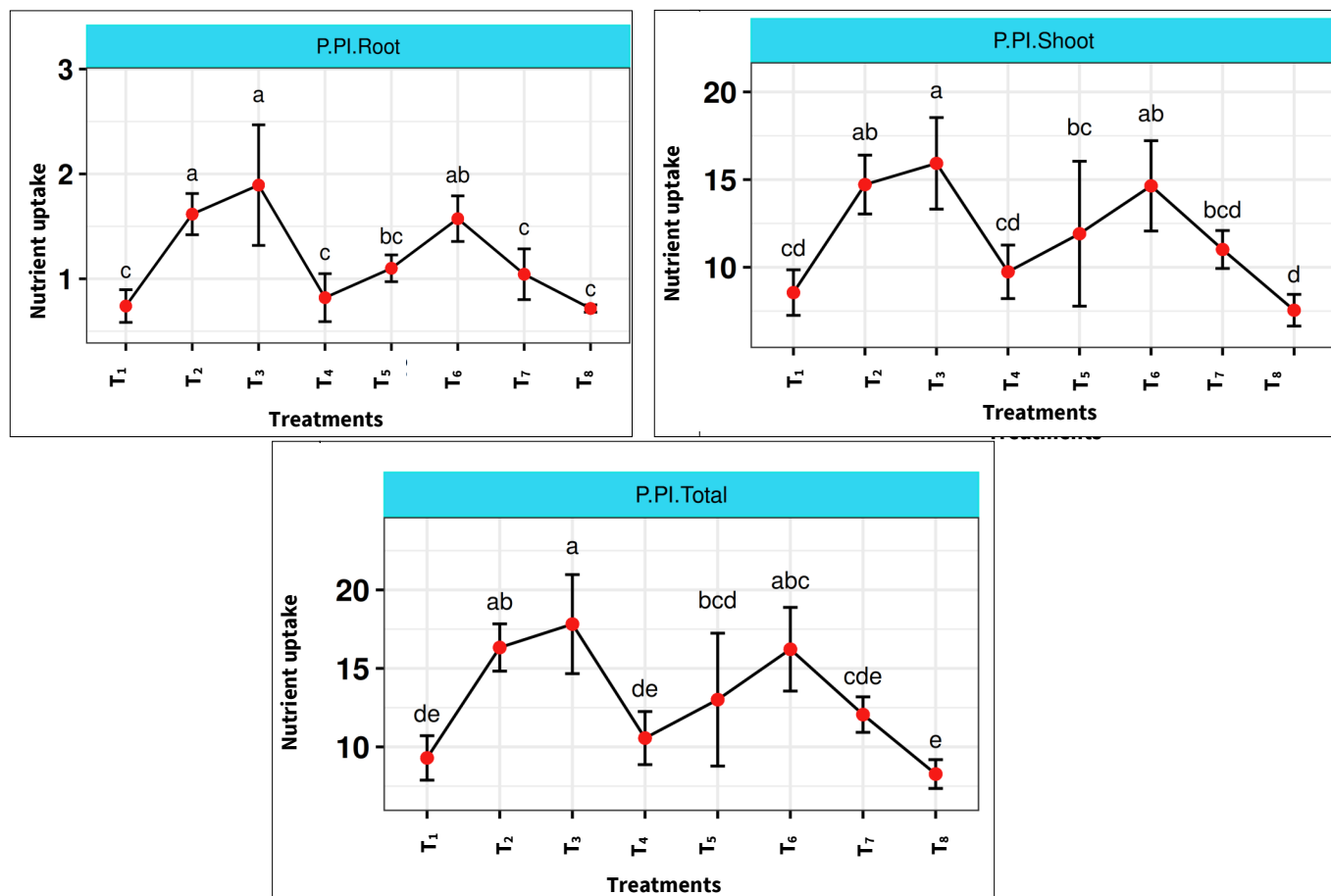


Fig. 2. Root, shoot and total phosphorus uptake at panicle initiation stage in kharif rice.

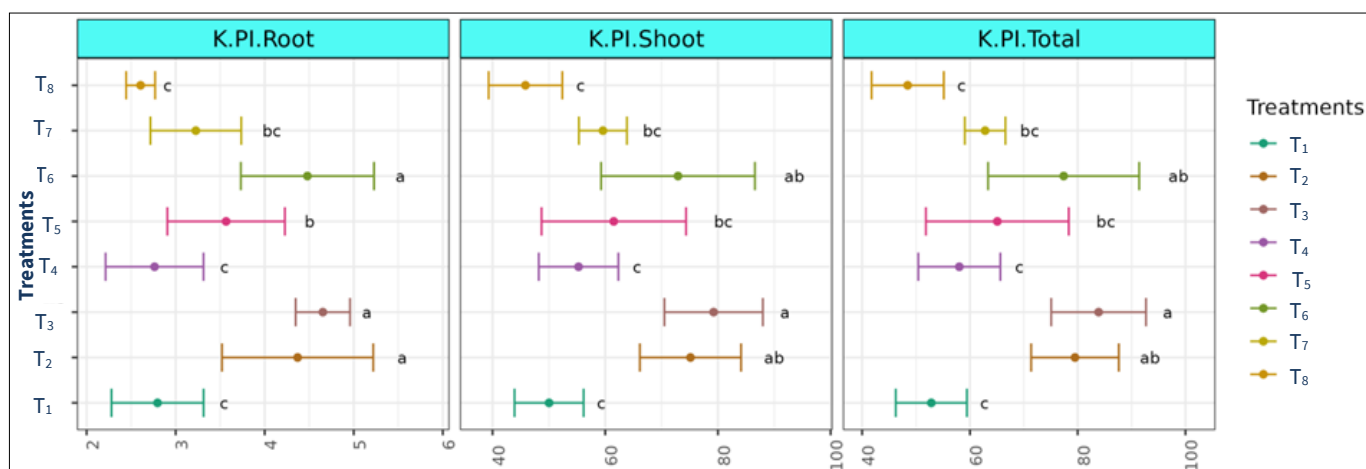


Fig. 3. Root, shoot and total potassium uptake at panicle initiation stage in kharif rice.

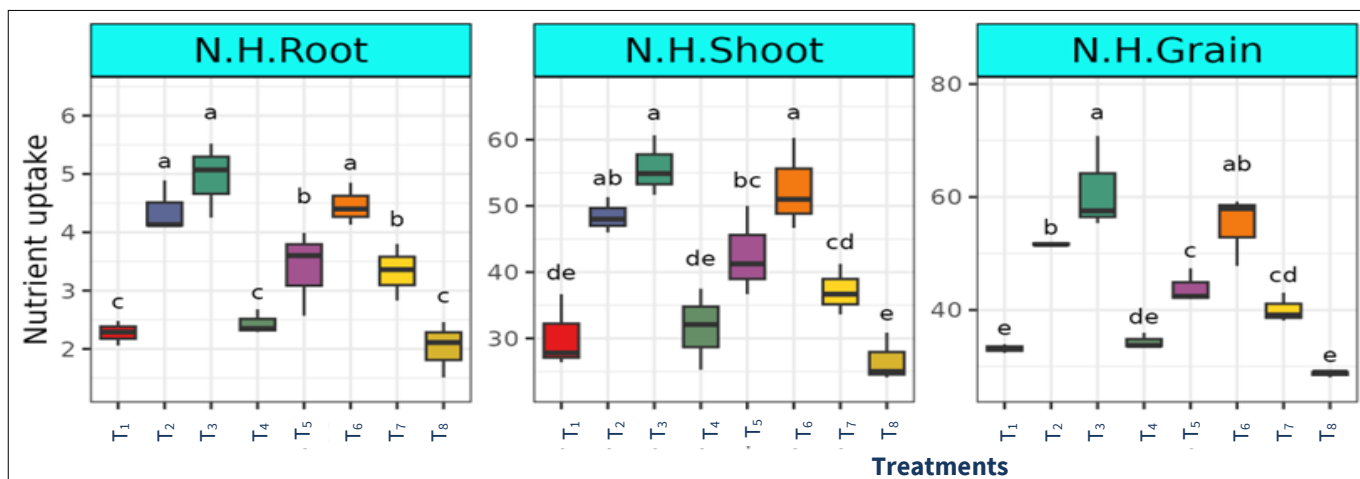


Fig. 4. Root, shoot and grain nitrogen uptake at harvest stage in kharif rice.

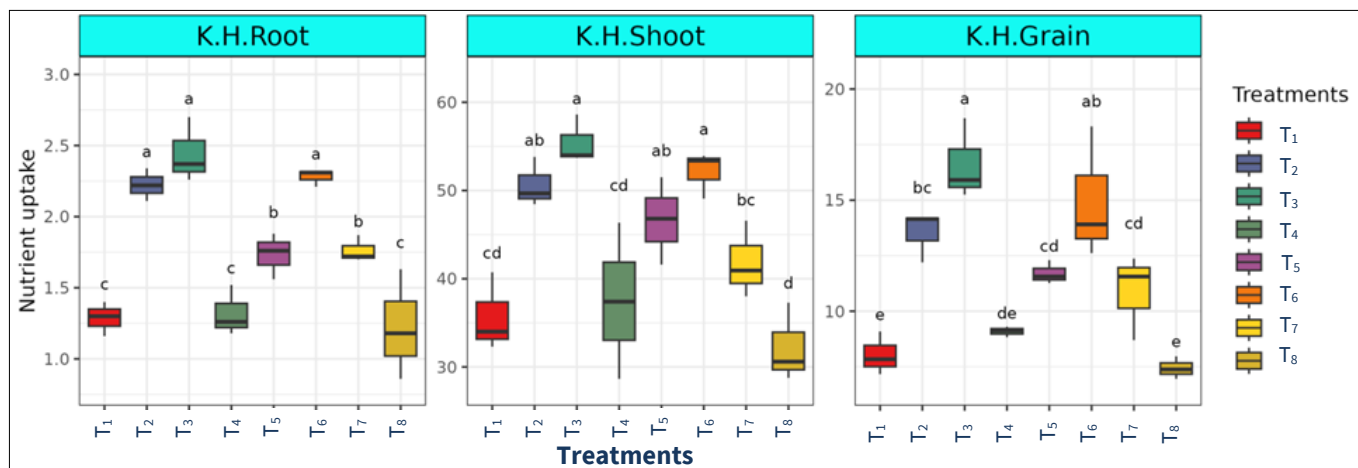


Fig.5. Root, shoot and grain potassium uptake at harvest stage in kharif rice.

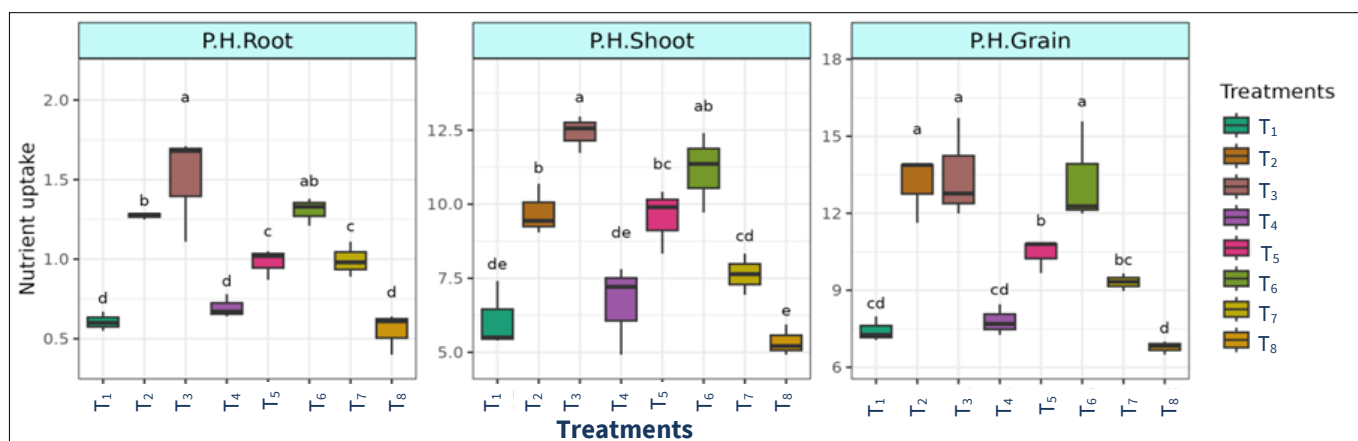


Fig. 6. Root, shoot and grain phosphorus uptake at harvest stage in kharif rice.

Discussion

Nano Zn nutrition markedly enhanced rice growth, yield formation and macronutrient uptake. Treatments involving nano Zn NP combined with foliar application at MT (T_3) and repeated foliar application at MT and PI (T_6) consistently performed better over the control and conventional $ZnSO_4$ treatments, demonstrating the superior efficiency of nano zinc under high-P soil conditions (Fig. 7).

Vegetative growth parameters such as plant height, tiller density and leaf area index responded positively to nano Zn application. Taller plants and increased tillering under T_3 and T_6 reflect improved Zn bioavailability and utilisation, as Zn is directly involved in tryptophan metabolism and indole-3-acetic acid

synthesis, which regulate cell elongation and meristematic activity (17, 18). Similar improvements in rice growth under adequate Zn nutrition have been reported earlier (15, 19), while nano Zn has been shown to enhance plant architecture through improved nutrient mobilisation and metabolic activity (7). Enhanced leaf area index under nano Zn treatments indicate improved canopy development and photosynthetic capacity, supported by Zn-mediated chlorophyll biosynthesis, membrane stability and oxidative stress protection (14, 20). Rapid foliar uptake of nano Zn by metabolically active tissues likely contributed to sustained leaf expansion and delayed senescence, consistent with earlier reports in field crops (21–23).

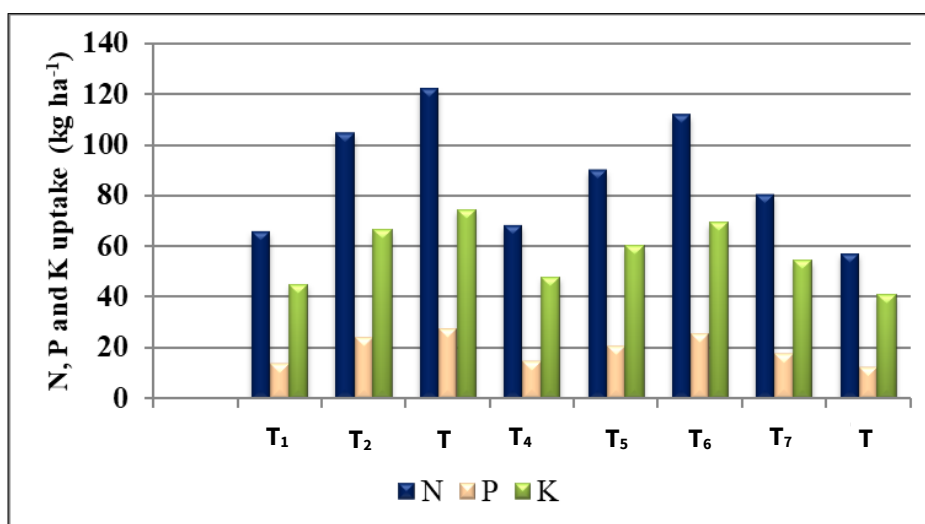


Fig. 7. Effect of nano zinc nutrition on nutrient uptake by different parts of rice plant at harvest stage during kharif, kg ha⁻¹.

Improved vegetative growth translated into enhanced yield formation under nano Zn nutrition. Higher productive tillers per hill and increased dry matter production indicate improved source strength and assimilate availability. Zinc-mediated activation of enzymes involved in photosynthesis, protein synthesis and carbohydrate metabolism likely enhanced biomass accumulation and assimilate translocation (8, 24). Reduced sterility percentage and increased number of grains per panicle under nano Zn treatments suggest improved reproductive efficiency, likely due to enhanced pollen viability, spikelet fertility and carbohydrate transport during grain filling (25, 26). Consequently, grain yield increased substantially under T₃ and T₆, recording 78.14 % and 68.72 % increase over the control, respectively in pooled analysis over the seasons. Straw yield also improved significantly, reflecting increased vegetative biomass and overall crop vigour (7, 27).

Nano Zn nutrition further enhanced macronutrient uptake. Improved nitrogen uptake under T₃, T₂ and T₆ at PI can be attributed to Zn-induced improvement in root system architecture and activation of enzymes involved in nitrogen metabolism, including nitrate reductase, glutamate dehydrogenase and asparaginase (28, 29). Early Zn availability through priming and foliar application promoted root proliferation and nitrogen uptake efficiency, as also reported in rice (17, 30). At harvest, higher nutrient uptake under T₆ compared with T₂ suggests that continued Zn supply through foliar application supported sustained nutrient acquisition and translocation to reproductive tissues (31).

Despite high soil P levels, P uptake was enhanced under nano Zn treatments, particularly T₃ and T₆. Improved Zn bioavailability may have enhanced root morphology, phosphatase activity and rhizosphere P mobilisation, while spatial and temporal separation of Zn and P uptake reduced antagonism (32–34). Potassium uptake also improved under nano Zn nutrition, reflecting Zn's role in maintaining membrane integrity and activating ATPase-mediated transport processes essential for K absorption and redistribution during reproductive growth (27, 35, 36).

Conclusion

Overall, the integrated improvement in vegetative growth, yield components and nutrient uptake under nano zinc (Zn) nutrition highlights its potential as an efficient Zn delivery strategy for rice. The superiority of nano Zn-based treatments over conventional Zn sources emphasises the importance of sustained and stage specific Zn availability for optimising crop performance in intensive rice production systems where phosphorus (P) induced Zn availability is more prominent. The effect of Zn nutrition for mitigating stress in rice plants could be studied in future line of work on rice based cropping system.

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Authors' contributions

BA conceptualised the study, conducted the field experiment, collected and analysed the data and prepared the manuscript. BJS contributed to the refinement of the experimental design and

reviewed the manuscript. SPP, JJ, MAV and PPG provided technical assistance, data interpretation and overall support in the execution of the study. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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