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Interactive Effects of Poultry Manure and Zinc on Growth, Productivity, and Nutrient Uptake of Rice under Indo-Gangetic Plain of West Bengal, India

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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

A field experiment was conducted during the rabi season of 2024 at Ghetugachi, Nadia, West Bengal, to evaluate the combined effects of poultry manure (PM) and zinc (Zn) application methods on rice growth, yield and nutrient uptake. The experiment followed a factorial randomised block design with three replications and 16 treatment combinations comprising four PM rates (0, 150, 250 and 500 g m^{-2}) and four Zn treatments (no Zn, basal zinc sulphate, foliar zinc sulphate and seedling root dipping in zinc oxide). Plant growth, yield attributes, grain and straw yields, and nutrient uptake were evaluated. Relationships among measured traits were examined using correlation analysis and principal component analysis (PCA). Poultry manure combined with Zn generally improved crop performance relative to the control. The highest grain yield (6.59 t ha^{-1}) occurred with 500 g m^{-2} PM and

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basal Zn application, representing an increase of 70.28% over the control. The same PM rate combined with foliar Zn produced the highest straw yield (6.18 t ha^{-1}; 59.68% increase) and Zn uptake (294.62 g ha^{-1}; 261.44% increase). Nitrogen, phosphorus and potassium uptake also improved under combinations involving higher PM rates and basal or foliar Zn application. The first two principal components explained 86.38% of the observed variation, with nutrient uptake and grain yield contributing strongly to the first component. These findings indicate that integrating PM with basal or foliar Zn application may improve rice productivity and nutrient uptake under the conditions evaluated.

Keywords: *Oryza sativa L.; poultry manure; zinc fertilisation; basal application; foliar application; root dipping; rice productivity; grain yield; nutrient uptake; principal component analysis.*

1. Introduction

Zinc (Zn) deficiency remains one of the most significant and overlooked limitations on both crop productivity and human health. Globally, an estimated 3 billion people are affected by insufficient Zn and iron intake, and roughly half a million children die each year as a consequence, with Zn-deficient soils remaining widespread worldwide, particularly under calcareous, high-p^H conditions (Hacisalihoglu, 2020). A similarly uneven pattern is evident in Indian soils: national soil-health survey data covering more than 30 million samples show that close to two-fifths of Indian soils are Zn deficient, with the burden ranging from under a tenth to over two-thirds of soils depending on the state, and Bihar and Odisha among the worst affected (Khokhar *et al.*, 2024). This soil-level deficiency may also have implications for human nutrition: India's Comprehensive National Nutrition Survey, the largest micronutrient survey of its kind conducted nationally, found low serum Zn in roughly a third of adolescents and approximately one in six preschool and school-age children, with the highest rates among children from rural, economically disadvantaged and less developed communities (Pullakhandam *et al.*, 2021).

Rice is central to this issue. Globally, it supplies approximately one-fifth of dietary energy and 14% of protein intake (Kennedy & Burlingame, 2003), and in India it remains the staple food for approximately two-thirds of the population while making up over 40% of national food-grain output. As grain Zn concentrations in cereals are influenced by Zn availability in the soils in which they are grown, and many rice-growing soils are Zn deficient, addressing this deficiency in rice is both an agronomic and a nutritional concern. Zinc-enriched rice may provide nutritional benefits beyond those associated with higher yields alone.

Several agronomic approaches have been evaluated successfully. Foliar Zn spray, evaluated recently against seed coating and soil application in both direct-seeded and transplanted rice, produced the tallest plants, the most productive tillers, and the highest yield among all methods tested, while more than doubling grain Zn concentration relative to the untreated control (Ijaz *et al.*, 2025). Method comparisons in aerobic rice have likewise shown that how Zn is applied, not just how much, influences the growth and yield response (Mondal *et al.*, 2020). In addition, root-dipping and soil-applied Zn treatments have produced consistent gains in both yield and grain Zn accumulation (Jatav *et al.*, 2019; Das *et al.*, 2019), and the wider research emphasis has shifted from yield alone toward grain nutritional quality as an explicit breeding and management target (Rasel *et al.*, 2023). Recent on-farm evaluations in eastern India have shown that zinc application in the nursery and after transplanting can produce different yield responses under site-specific nutrient management (Mishra *et al*., 2025). Comparative work on basmati rice has also reported differences between soil and foliar zinc application in micronutrient uptake, reinforcing the need to consider the application method (Sardar *et al*., 2024). A second, less-studied aspect concerns organic amendments, particularly poultry manure (PM), a relatively nutrient-rich and rapidly mineralising organic amendment. Using poultry manure alongside Zn has been reported to outperform either input used alone. In Zn- and iron-enriched organic manure trials on sodic soil, enriched PM produced the tallest plants, the most tillers, and the greatest biomass among the organic sources compared, outperforming vermicompost and farmyard manure at matching Zn levels (Sankavi *et al.*, 2020). When Zn and PM were used together on aromatic fine rice, the plants exhibited greater height, produced more productive tillers and developed heavier grains. The highest yield was obtained by combining Zn and poultry manure at appropriate levels rather than by applying either input alone (Rasel *et al.*, 2023). Poultry manure's residual effect alone has also been shown to increase grain Zn, Cu, N and protein contents relative to untreated controls, with the gains scaling directly with manure dose (Das *et al.*, 2024). Together, these results suggest a possible interaction rather than two independent additive effects. Evidence from transplanted rice grown in acidic soil further suggests that the combination of zinc fertilization with biological nutrient inputs can influence grain yield and grain zinc concentration (Debnath *et al*., 2026).

The cropping system provides further context. When rice is grown twice annually in the same fields, repeated nutrient removal may influence soil Zn availability over time, which cannot be evaluated fully in a single-season study. A recent three-year study of rice–rice cropping found that combining farmyard manure with chemical fertilizer maintained higher yields, soil carbon and populations of beneficial soil microorganisms than either input used alone (Paramesh *et al.*, 2023). This suggests that combining organic and inorganic inputs may become increasingly important as cropping intensifies. A field investigation in a rice–wheat system also showed that the choice of zinc management strategy can affect rice yield, zinc uptake, and residual soil zinc status (Upadhyay *et al*., 2026).

In this context, limited research has examined how different application methods of Zn interact with graded doses of poultry manure in moderately Zn-deficient lowland rice, especially when their combined effects on yield and nutrient uptake are analysed jointly. To address this gap, we conducted a factorial experiment comparing four Zn application methods (no Zn, basal soil application, foliar spray and root dipping) crossed with four poultry manure doses in rice grown on a moderately Zn-deficient soil. The objectives were to examine: (i) how different methods of Zn application (basal, foliar, and root dipping) interact with graded poultry manure doses to influence rice yield and Zn biofortification, and (ii) whether these interactions influence vegetative traits, yield components, and nutrient uptake. By integrating a full factorial assessment of four Zn methods × four PM doses with multivariate analysis of yield and nutrient uptake, this work goes beyond single-factor experiments and provides further insight into how integrated Zn and organic nutrient management can be improved for rice grain quality and productivity.

2. Materials and Methods

2.1 Site of Experiment

A field study was carried out during the *rabi* season of 2024 in a farmer's field at Ghetugachi, Simurali, Nadia, West Bengal, using the rice variety Satabdi. The experimental site was located at latitude 23.03˚ N and longitude 88.58˚ E. Ghetugachi has a humid and warm climate with a temperature range of 19 to 32 ˚C, a relative humidity of 70-90% during the *rabi* season (January to May) (Fig. 1). The study was conducted on an Inceptisol soil described as silty clay (Typic Haplusteps). Soil samples were collected from the field, dried, ground, sieved and stored in a dry container. Soil parameters were analysed using standard protocols before the experiment. The physicochemical properties of the experimental plot soil (Table 1) were analysed using an established procedure (AOAC, 2006).

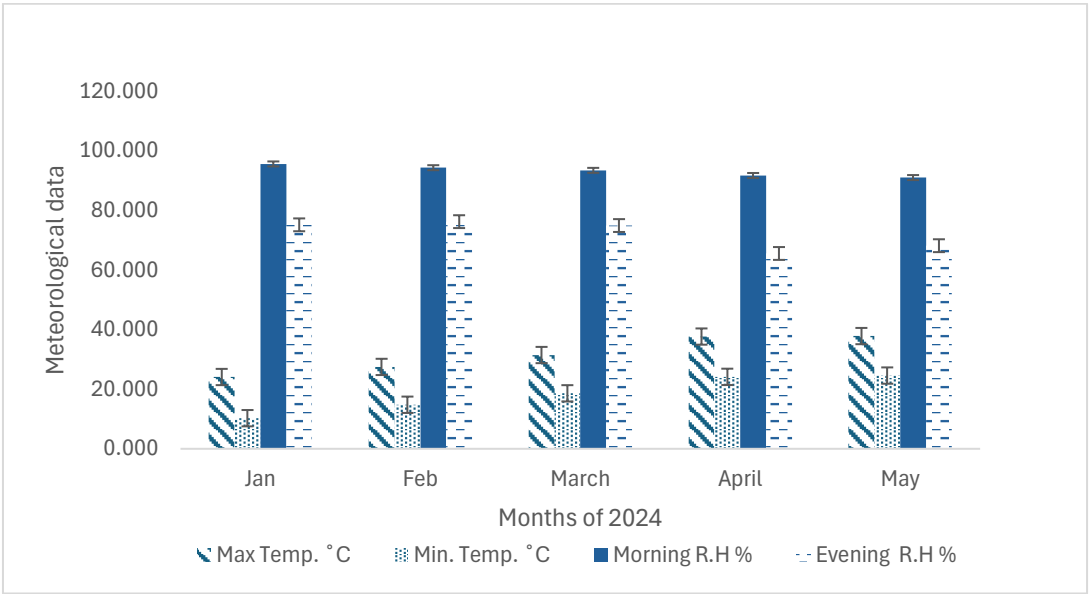


Fig. 1a.

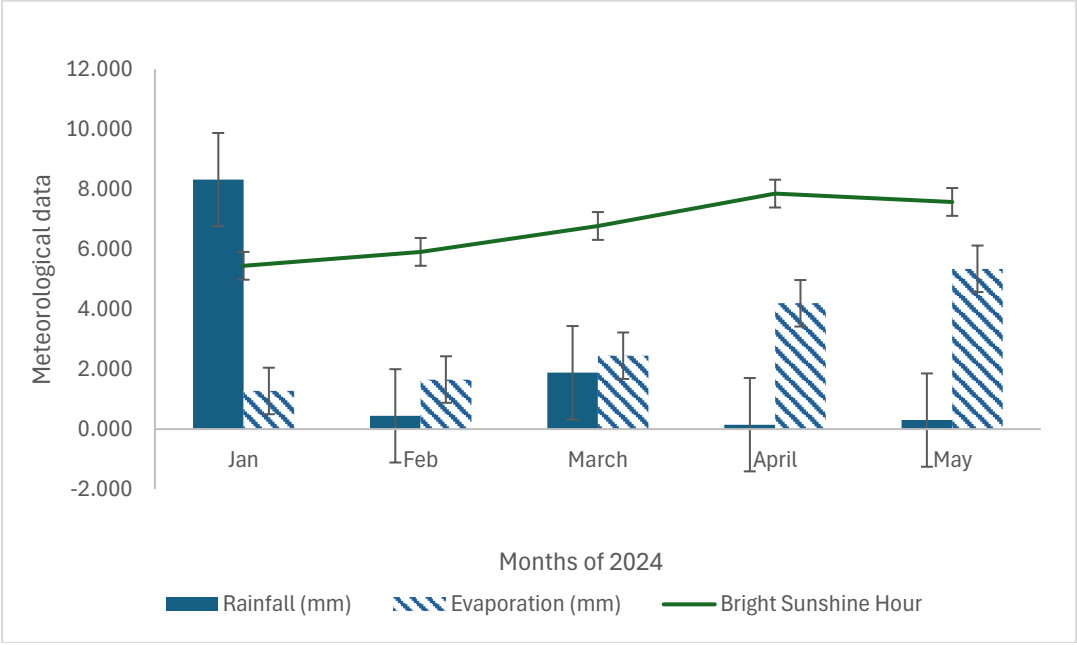


Fig. 1b.

Fig. 1. a-b Meteorological data during field experiment of 2024

2.2 Experimental Details and Treatments

This study was conducted in an experimental field using the rice variety *satabdi* as the test crop. It used a two-factor factorial RBD comprising 16 treatments and three replications. Each experimental plot measured 2 × 2 m^2. Rice seeds were sown in the nursery bed in late December. After 35 days, seedlings were transplanted into the farmer's field and kept under submerged conditions. Plant growth and development data were subsequently recorded at different days after transplanting (DAT). Based on recommendations from the ICAR-National Rice Research Institute, Cuttack, India, the fertiliser dose for rice in West Bengal is N: P_2O_5: K_2O= 120:60:60 kg ha^{-1}. Accordingly, nitrogen, phosphorus and potassium fertilisers were applied to each treatment. Urea, muriate of potash and single superphosphate were used as sources of N, P and K in all treatments.

The factorial treatments comprised four doses of PM, namely P_1- 0, P_2- 150, P_3- 250, P_4- 500 g m^{-2} and four Zn application methods, namely Z_1- no Zn, Z_2- basal application of $ZnSO_4$ ($ZnSO_4$. H_2O- 33% Zn) @ 10 kg ha^{-1}, Z_3- foliar application of $ZnSO_4$ ($ZnSO_4$. H_2O- 33% Zn) (@ 0.5% at maximum tillering stage and Z_4- root dipping of seedlings in ZnO solution (ZnO-80% Zn) @ 2%. The nutrient contents of PM were 1.31% N, 0.86% P and 2.14% K.

Table 1. Physico-chemical characteristics of initial soil of experimental field

Parameters	Value
Sand (%)	15.2
Silt (%)	42.5
Clay (%)	29.6
Textural class	Silty clay loam
p^H (1:2.5)	6.69
Electrical conductivity (EC) (dSm^{-1})	0.45
Oxidisable organic carbon (%)	0.73
$KMnO_4$-N (kg ha^{-1})	285.36
Olsen P (kg ha^{-1})	28.37
Neutral normal NH_4OAc- K (kg ha^{-1})	267.16
DTPA extractable-Zn (mg kg^{-1})	0.55

2.3 Growth and Yield Attributes of Rice

Rice growth and yield parameters, including plant height and number of tillers, were measured at 30, 60, and 90 days after transplanting (DAT). At maturity, observations were recorded for the number of grains per panicle. After removing the panicles, plants were harvested by cutting them 5 cm above the ground to prevent soil contamination. The harvested plants were successively cleaned with 0.2% detergent solution, 0.1 N HCl, and finally with double-distilled water, and the plant samples were then dried in a hot air oven (60°C) until a constant weight was achieved. Data on grain and straw yields and test weight were recorded for further analysis.

2.4 Soil and Plant Analysis

Before the trial started, soil surface soil samples (0-15 cm) were taken from five separate locations, combined to form a composite sample, and then processed using conventional protocols: soil texture (Piper, 1966), p^H and EC (Jackson, 1973), oxidizable organic carbon (Walkley & Black, 1934), available nitrogen (Subbiah & Asija, 1956), available phosphorus (Olsen *et al*., 1954), available potassium (Jackson, 1973) and available Zn (Lindsay & Norvell, 1978).

Composite plant samples were collected from each plot at harvest. The samples were first washed with 0.1 N HCl and then rinsed with deionised water. Afterwards, they were sun-dried, separated into grain and straw portions, and further oven-dried for 48 hours at 65 ± 5 °C. The dry materials were finely ground using a Willey grinder. The powdered samples were then digested with a tri-acid mixture of nitric acid, perchloric acid, and sulfuric acid in a 10:3:1 ratio. The concentrations of Zn were determined following the methods outlined by Tandon (1993).

2.5 Statistical Analysis

The data were evaluated using analysis of variance (ANOVA) in SPSS and the R software package, following standard procedures. Additionally, Duncan's multiple range test (DMRT), at a significance level of < 0.05, was used to assess differences among the mean values.

3. Results and Discussion

3.1 Impact on Plant Growth Parameters

Plant height, filled grains per panicle, tillers per hill, test weight, chlorophyll content and leaf area index of rice were significantly (p< 0.05%) affected by poultry manure (PM) and different Zn application methods. Plant heights at the 30 and 90 DAT stages were significantly improved relative to the control treatment by organic matter and Zn amendments, whereas no significant effect was observed at 60 DAT (Fig. 2). Across treatments, rice plant height at 30, 60 and 90 DAT increased by up to 42.37% over control. The increase in filled grains per panicle ranged from 5.26 to 65.41%, whereas the increases in tillers per hill and test weight ranged from

15.03 to 155.05% and 5.56 to 38.89%, respectively, relative to the control (Table 2). 500 g m^{-2} PM + root dipping of ZnO (P4Z4) and 500 g m^{-2} PM + foliar application of $ZnSO_4$ (P4Z3) treatments resulted in the highest plant height at 30 DAT and 90 DAT respectively. Zinc application significantly affects plant height at different growth stages, but the magnitude of the response varies, increasing with growth up to anthesis and subsequently slowing (Mandal & Ghosh, 2021).

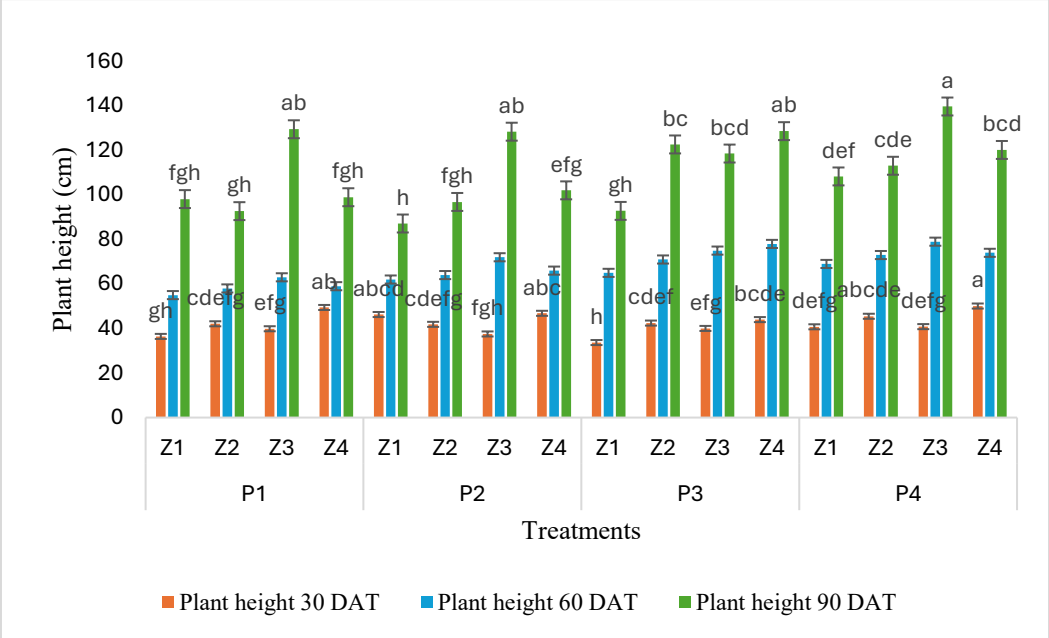


Fig. 2. Effect of graded doses of PM and different methods of Zn application on plant heights of rice

Among the PM treatments, the P4 level showed the highest number of filled grains ($p < 0.05\%$). Root dipping (Z4) showed a significant ($p < 0.05\%$) increase in grain number, which was statistically at par with foliar application (Z3). The number of tillers and test weight also increased with increasing poultry manure doses. Tillers $hill^{-1}$ and grain test weight were significantly ($p < 0.05\%$) higher under root dipping (Z4) and foliar (Z3) Zn applications, respectively. The interaction between these two factors was also significant for the growth parameters. These findings are in close agreement with the results of Hossain *et al.* (2008) and Wang *et al.* (2014) on Zn application.

3.2 Impact on Yield of Grain and Straw

Rice grain yield was significantly affected by PM levels, Zn application methods, and their interaction. Rice grain yield increased significantly, ranging from 12.40 to 59.17% over the control. Straw yield improvements relative to the control plot ranged from 13.44 to 51.10%. Grain yield increased with increasing PM, from 4.18 t ha^{-1} at P1 to 5.48 t ha^{-1} at P4. Among the Zn treatments, basal application (Z2) showed the maximum yield (5.41 t ha^{-1}), statistically at par with foliar application (Z3), whereas the control (Z1) produced a lower yield. The interaction outcome was significant ($p<0.05\%$), with 500 g m^{-2} PM + basal application of $ZnSO_4$ (P4Z2) producing the highest rice grain yield (6.59 t ha^{-1}, 70.28% increase), suggesting an interaction between the higher manure rate and basal Zn application. Foliar application (Z3) gave the highest straw yield (5.49 t ha^{-1}), followed by root dipping (Z4), while the control (Z1) was the lowest (4.26 t ha^{-1}). The interaction was significant, with 500 g m^{-2} PM + foliar application of $ZnSO_4$ (P4Z3) producing the highest yield (6.18 t ha^{-1}, a 59.68% increase) and (150 g m^{-2} PM + no Zn) P2Z1 producing the lowest (4.07 t ha^{-1}) (Table 3).

The grain and straw yield results are consistent with the findings of Kandil *et al.* (2022). Furthermore, poultry manure increased rice grain yield by 67.3% and 61.4% over control across two years (Kaur *et al*., 2023).

3.3 Impact on Macro Nutrient Uptake

N, phosphorus and K uptake all increased significantly ($p < 0.05$) with rising PM and Zn levels, following broadly similar dose-dependent patterns. N uptake rose from 6.52 kg ha^{-1} (P1) to 9.81 kg ha^{-1} (P4) and from 6.84 kg ha^{-1} (Z1) to 8.65 kg ha^{-1} (Z3), with the PM × Zn interaction showing the lowest uptake in P1Z1 (6.00 kg ha^{-1}) and the highest in P4Z3 (11.01 kg ha^{-1}, 83.59% increase). Similarly, P uptake increased from 0.79 kg ha^{-1} (P1) to 1.08 kg ha^{-1} (P4) and from 0.79 kg ha^{-1} (Z1) to 1.03 kg ha^{-1} (Z3), peaking at 500 g m^{-2} poultry manure + basal application of $ZnSO_4$ (P4Z2) (1.21 kg ha^{-1}, 74.03% increase). K uptake followed the same trend, rising from 3.95 kg ha^{-1} (P1) to 6.91 kg ha^{-1} (P4) and from 4.39 kg ha^{-1} (Z1) to 5.83 kg ha^{-1} (Z3), with the maximum recorded in P4Z2 (7.96 kg ha^{-1}, 124.04% increase) (Fig. 3). The substantial increases in nitrogen, phosphorus and potassium uptake with basal and foliar Zn application compared with root dipping and no Zn indicate that better Zn nutrition improves overall plant growth and the capacity to acquire primary nutrients (Ghasal *et al.*, 2015; Singson *et al.*, 2021).

Table 2. Effect of graded doses of PM and different methods of Zn application on filled grains panicle^{-1} (cm), tillers hill^{-1} and test weight (g)

Treatments	Filled grains panicle^{-1} (cm)					Tillers hill^{-1}					Test weight (g)				
	Z1	**Z2**	**Z3**	**Z4**	**Mean**	**Z1**	**Z2**	**Z3**	**Z4**	**Mean**	**Z1**	**Z2**	**Z3**	**Z4**	**Mean**
P1	66.50	81.00	90.00	85.50	80.75c	9.99	12.99	13.5	18.5	13.74c	18	19	20.5	19.5	19.25c
P2	70.00	95.00	92.50	86.50	86.00bc	11.5	16	22.99	19.5	17.49ab	19.5	20.5	23	21	21.00b
P3	78.50	86.40	91.60	110.00	91.63ab	12.5f	16	20.5	25.49	18.62a	20.5	21.5	22.5	24	22.12ab
P4	87.50	87.50	102.50	110.00	96.88a	12.5	16	20.5	25.49	17b	21.5	22.5	25	23	23a
Mean	75.62c	87.48b	94.15a	98.00a		12.12d	14.75c	18.87b	21.12a		19.88c	20.87bc	22.75a	21.87ab	
	SEm	CD (p<0.05)				SEm	CD (p<0.05)				SEm	CD (p<0.05)			
PM	1.98	5.71				0.46	1.33				0.52	1.50			
Zn	1.98	5.71				0.46	1.33				0.52	1.50			
PM× Zn	3.95	11.41				0.92	2.66				1.039	NS			

[Z1= control, Z2= Basal application of $ZnSO_4$ @ 10 kg ha^{-1}, Z3= Foliar application of $ZnSO_4$ @ 0.5% at maximum tillering stage and Z4= Root dipping of seedling in ZnO solution @ 2%, P1=0, P2= 150, P3= 250 and P4= 500g m^{-2} of PM]

Table 3. Effect of graded doses of PM and different methods of Zn application on Grain yield (t ha^{-1}) and Straw yield (t ha^{-1})

Treatments	Grain yield (t ha^{-1})					Straw yield (t ha^{-1})				
	Z1	**Z2**	**Z3**	**Z4**	**Mean**	**Z1**	**Z2**	**Z3**	**Z4**	**Mean**
P1	3.87	4.35	4.29	4.22	4.18c	4.09	4.64	4.96	5.53	4.80
P2	4.01	5.80	4.55	4.72	4.77b	4.07	4.76	5.03	5.20	4.76
P3	3.99	4.89	5.57	4.82	4.82b	4.25	5.31	5.77	4.69	5.00
P4	4.12	6.59	6.16	5.06	5.48a	4.64	5.24	6.18	4.56	5.15
Mean	4.00c	5.41a	5.14a	4.71b		4.26c	4.99b	5.49a	5.00b	
	SEm	CD (p<0.05)				SEm	CD (p<0.05)			
PM	0.13	0.37				0.127	NS			
Zn	0.13	0.37				0.127	0.366			
PM× Zn	0.26	0.73				0.253	0.731			

[Z1= control, Z2= Basal application of $ZnSO_4$ @ 10 kg ha^{-1}, Z3= Foliar application of $ZnSO_4$ @ 0.5% at maximum tillering stage and Z4= Root dipping of seedling in ZnO solution @ 2%, P1=0, P2= 150, P3= 250 and P4= 500g m^{-2} of poultry manure]

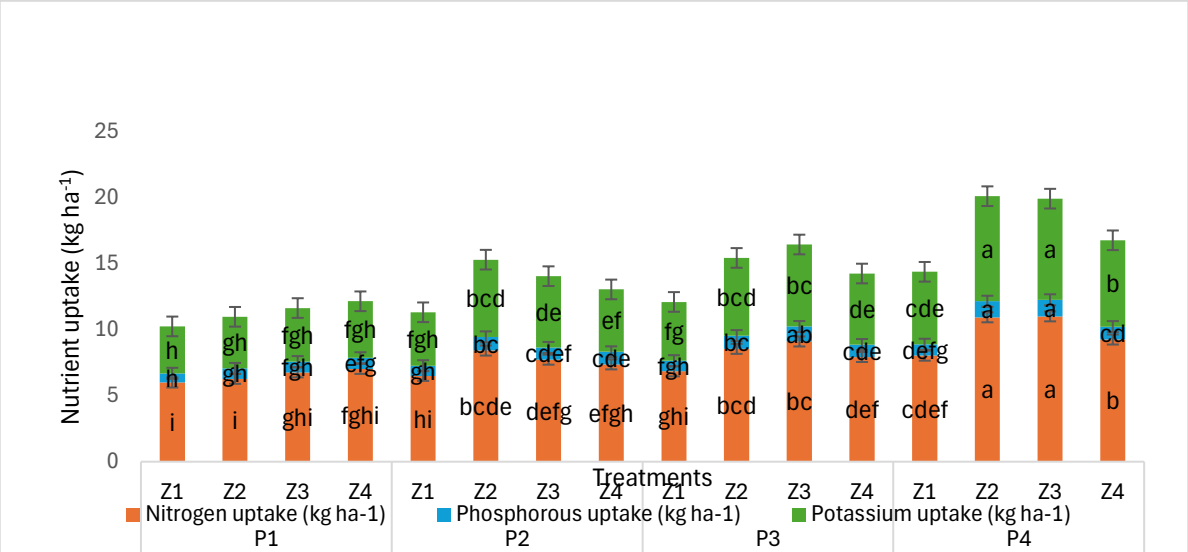


Fig. 3. Effect of graded doses of PM and different methods of Zn application on macronutrient uptake

3.4 Impact on Zn Uptake

Zn uptake in rice increased significantly (p<0.05%) with organic manure and Zn application. Zn uptake ranged from 81.51 to 294.62 g ha^{-1}. Among the poultry manure doses, P4 showed the greatest (175.65% increase) Zn enrichment in rice (Table 4).

Table 4. Effect of graded doses of PM and different methods of Zn application on Zn uptake (g ha^{-1})

Treatments	Zn uptake (g ha^{-1})				
	Z1	**Z2**	**Z3**	**Z4**	**Mean**
P1	81.51	85.78	112.74	117.38	99.35d
P2	105.30	149.58	160.04	150.05	141.24c
P3	126.65	173.04	225.09	171.54	174.08b
P4	162.17	219.34	294.62	222.60	224.68a
Mean	118.91c	156.94b	198.12a	165.39b	
	SEm	CD			
PM	4.17	12.03			
Zn	4.17	12.03			
PM× Zn	8.33	24.06			

[Z1= control, Z2= Basal application of $ZnSO_4$ @ 10 kg ha^{-1}, Z3= Foliar application of $ZnSO_4$ @ 0.5% at maximum tillering stage and Z4= Root dipping of seedling in ZnO solution @ 2%, P1=0, P2= 150, P3= 250 and P4= 500 g m^{-2} of PM]

Foliar application (Z3) showed the highest Zn uptake (a 143.06% increase) among the treatments, followed by basal (Z2) and root dipping (Z4), which were statistically at par. The interaction was significant (p<0.05%); 500 g m^{-2} poultry manure + foliar application of $ZnSO_4$ (P4Z3) increased Zn uptake by 261.44% relative to the control (Fig. 4). Among Zn application methods, foliar application (Z3) produced the highest Zn uptake, followed by basal (Z2) and root dipping (Z4), and their interaction with poultry manure was significant. The greater uptake under foliar Zn application may further be associated with the direct absorption of Zn through leaves, which can partially bypass soil-related constraints such as Zn fixation and poor availability under flooded conditions. Foliar Zn has been reported to enhance nutrient uptake and recovery in rice, particularly when integrated with organic or biological nutrient sources. The stronger response at higher poultry manure levels therefore suggests a synergistic interaction between organic manure and Zn fertilization, in which improved soil nutrient availability and plant physiological activity enhanced nutrient absorption and translocation (El-Sobky *et al.*, 2022; Yogi *et al.*, 2023).

3.5 Correlation between Growth Parameters and Nutrient Uptake

Pearson correlation analysis of ten growth, yield and nutrient uptake parameters revealed predominantly strong, positive and highly significant relationships, indicating close physiological associations among these traits.

Plant height exhibited significant positive correlations with test weight (r = 0.82, p < 0.001) and number of grains per panicle (r = 0.71, p < 0.01), whereas tillers were strongly correlated with test weight (r = 0.73, p < 0.01) and grains per plant (r = 0.81, p < 0.001). However, yield of grain showed weak and non-significant associations with plant height (r = 0.44) and tiller number (r = 0.31), suggesting that these vegetative traits contribute only indirectly to net yield.

The strongest correlations occurred among nutrient uptake parameters, for N, P, K and Zn uptake (r = 0.92-0.99, p < 0.001), reflecting a closely associated nutrient-accumulation system rather than nutrient-specific uptake mechanisms. Grain yield was very

strongly correlated with nutrient uptake, particularly P uptake (r = 0.95, $p < 0.001$), N uptake (r = 0.91, $p < 0.001$), and K uptake (r = 0.90, $p < 0.001$), exceeding its correlations with straw yield (r = 0.63) or vegetative growth traits. However, yield of grain was weakly and non-significantly correlated with plant height (r = 0.44) and tiller number (r = 0.31), indicating that these vegetative traits were associated with yield mainly indirectly (Fig. 5) (Fageria & Oliveira, 2014).

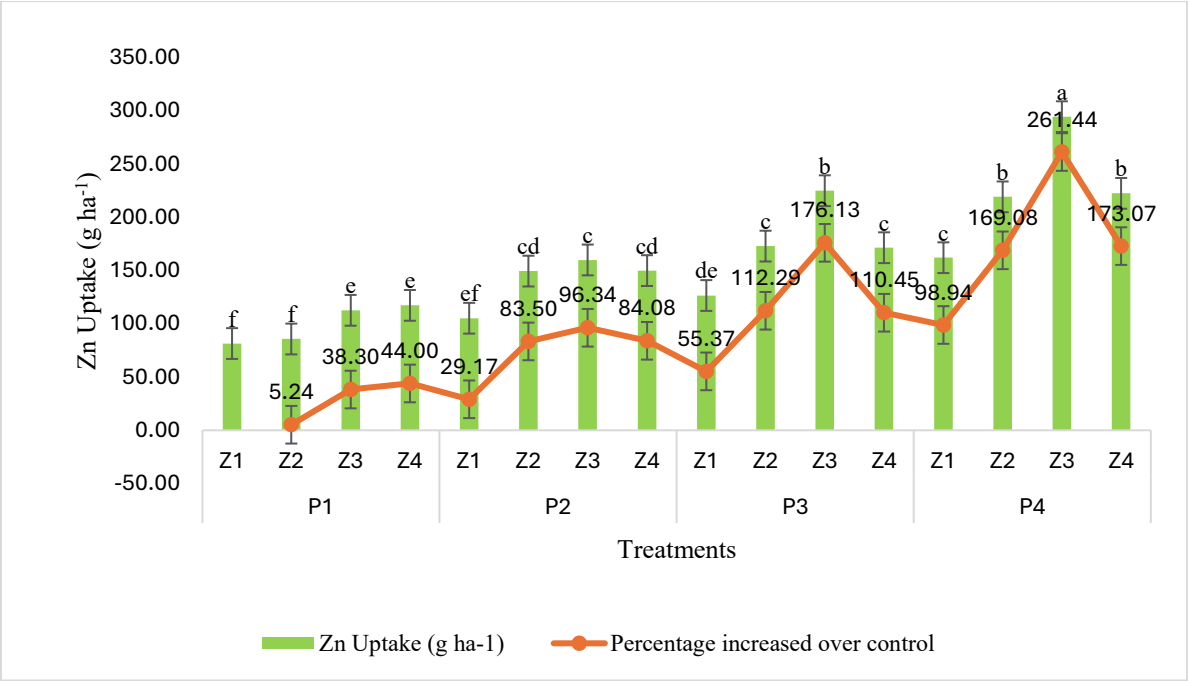


Fig. 4. Effect of graded doses of PM and different methods Zn application on Zn uptake and percentage increased

3.6 Principal Component Analysis (PCA)

Principal component analysis (PCA) was performed on ten morpho-physiological, yield, and nutrient-uptake traits recorded across the 16 poultry manure × Zn treatment combinations, to identify the principal axes of variation and characterise the differential response of the crop to graded levels of poultry manure and methods of Zn application. The analysis identified two principal components (PCs) with eigenvalues greater than unity, following Kaiser's criterion. These were regarded as the main axes of variation and together accounted for 86.38% of the total variance.

PC1 alone accounted for 72.69% of the total variance and showed positive loadings for every trait examined, with the highest loadings recorded for K uptake (K_U, 0.923), grain yield (Grain_Y, 0.917) and N uptake (N_U, 0.917), closely followed by phosphorus uptake (P_U, 0.882) and Zn uptake (Zn_U, 0.794) (Table 5). This loading pattern identifies PC1 principally as a nutrient-uptake-productivity axis, reflecting the coordinated response of grain yield and N, P, K, and Zn assimilation to Zn nutrition. PC2, explaining 13.69% of the variance, loaded highest on tiller number (Tillers, 0.938) and grain number (Grains, 0.81), representing a distinct reproductive trait axis largely independent of the nutrient-uptake gradient captured by PC1.

Table 5. Loadings (eigenvectors) of correlation matrix of the important principal components (PCs) of the variables related to crop development and nutrient uptake

Parameters	PC1	PC2
Plant_ht	0.262	0.408
Test_Wt	0.568	0.588
Tillers	0.107	**0.938**
Grains	0.39	0.81
Grain_Y	0.917	0.167
Straw_Y	0.425	0.202
Zn_U	0.794	0.333
N_U	0.917	0.194
P_U	0.882	0.245
K_U	**0.923**	0.225
eigenvalue	7.27	1.37
% of variance	72.69	13.69
Cummulative % of variance	72.69	86.38



Fig. 5. Correlation among different growth parameters and nutrient uptake

*[Where, Plant_ht = Plant height at harvesting, Test_wt= Test weight, Tillers= Tillers hill^{-1}, Grains= Grains panicle^{-1}, Grain_Y= Grain yield, Straw_Y= Straw yield, Zn_U= Zn uptake, N_U= N uptake, P_U= P uptake, K_U= K uptake; *, ** and *** denote significance at 0.05%, 0.01%, and 0.001% levels]*

The PCA biplot (Fig. 6) separated treatments along Dim1 (PC1). Treatments receiving the no-Zn treatment (Z1)- P1Z1, P2Z1, P3Z1, and, to a lesser extent, P4Z1- clustered in the negative (left) region of the biplot at each poultry manure level, indicating consistently poor nutrient-uptake and yield performance in the absence of adequate Zn supply. In contrast, treatments combining higher organic levels with Zn application methods- P4Z3, P4Z2, P3Z3, P4Z4, and P3Z4- occupied the positive (right) region, in close alignment with the Zn_U, K_U, P_U, N_U, and Grain_Y vectors, indicating higher nutrient uptake and yield. Along Dim2 (PC2), P3Z4 and P2Z3 occupied the extreme positive positions, aligning with the Tillers and Grains vectors and indicating a comparatively higher tillering and grain-number response, whereas P4Z2 occupied the extreme negative position on this axis despite a strongly positive PC1 score, suggesting that its superior nutrient uptake and yield were not accompanied by a proportionate increase in tiller or grain number.

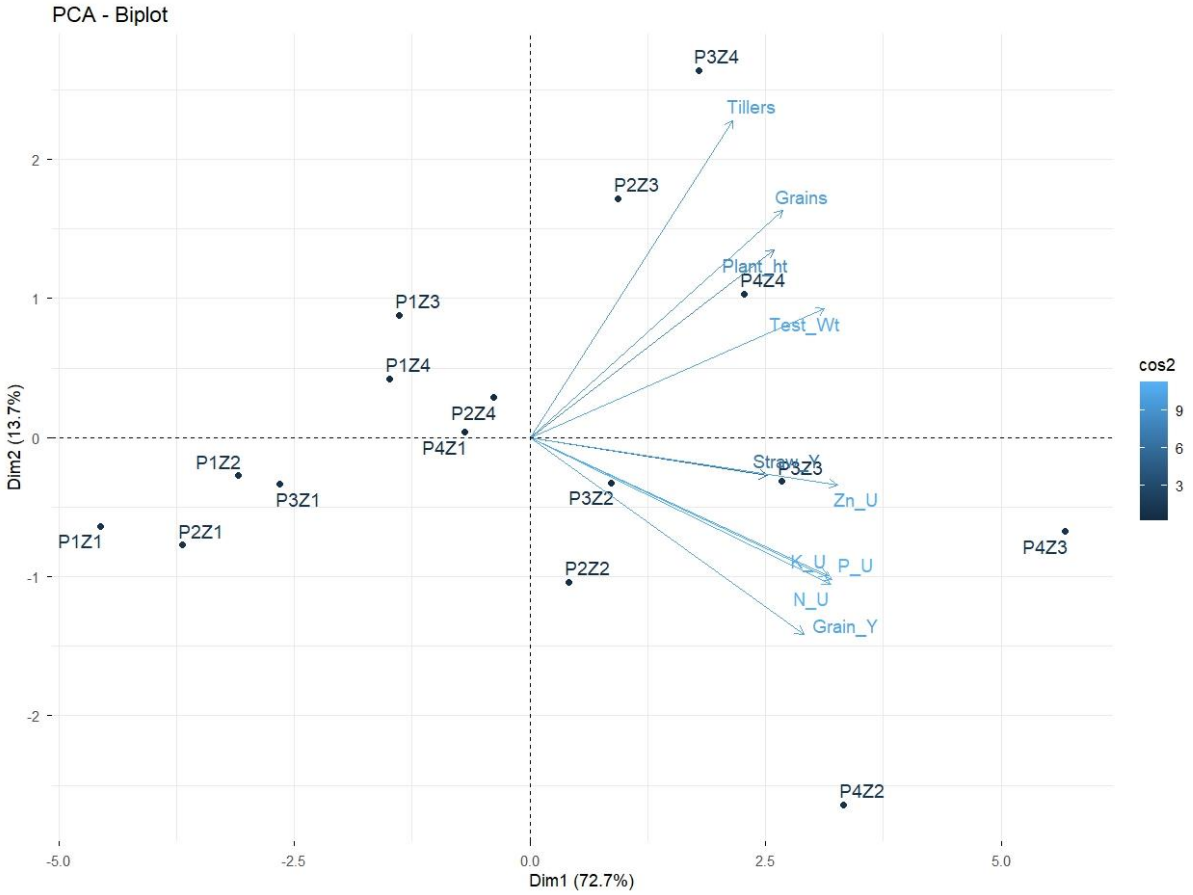


Fig. 6. Principal components analysis of a biplot showing the factors associated to crop growth and nutrient uptake

Table 6. Score of Principle component under different treatments of PM and methods of Zn application

Treatments	PC1	Ranking	PC2	Ranking
P1Z1	-4.556	16	-0.638	12
P1Z2	-3.093	14	-0.275	8
P1Z3	-1.382	11	0.880	4
P1Z4	-1.492	12	0.422	**5**
P2Z1	-3.685	15	-0.773	14
P2Z2	0.408	8	-1.040	15
P2Z3	0.930	6	1.714	2
P2Z4	-0.388	9	0.288	6
P3Z1	-2.650	13	-0.334	10
P3Z2	0.860	7	-0.325	11
P3Z3	2.677	3	-0.314	9
P3Z4	1.790	5	**2.638**	**1**
P4Z1	-0.696	10	0.042	7
P4Z2	3.327	2	-2.641	16
P4Z3	**5.677**	**1**	-0.675	13
P4Z4	2.272	4	1.030	3

Principal component scores (Table 6) reinforced these biplot-based inferences. P4Z3 recorded the highest PC1 score (5.677), followed by P4Z2, P3Z3, and P4Z4, whereas P1Z1, P2Z, and P3Z1 recorded the lowest scores. This indicates that the combination of higher poultry manure with Zn application (Z3-Z4) most strongly promoted the yield and nutrient-uptake complex represented by PC1, while Zn-deficient (Z1) treatments performed poorest irrespective of poultry manure level. On PC2, P3Z4 (2.638) and P2Z3 attained the highest positive scores, indicating the strongest reproductive trait response, while P4Z2 recorded the lowest score. Overall, the PCA suggests that Zn application, particularly through the Z3-Z4 methods, was an important contributor to enhanced nutrient uptake and grain yield in this experiment, while its influence on tillering, plant height, and straw yield followed comparatively independent, secondary trajectories.

Principal component analysis supported this interpretation. PC1 accounted for 72.69% of the total variance and loaded strongly on K uptake, grain yield, N uptake, P uptake and Zn uptake, identifying it as a nutrient-uptake-productivity axis. PC2 explained 13.69% of the variance and loaded mainly on tiller number and grains, representing a reproductive trait axis largely independent of PC1. Treatment combinations involving higher PM rates and Zn application (especially P4Z3, P4Z2, P3Z3 and P4Z4) scored highest on PC1 and grouped with the nutrient-uptake and grain-yield vectors, whereas Zn-deficient treatments (Z1) consistently occupied the negative side of PC1 irrespective of manure level. This supports the view that in this moderately Zn-deficient rice field, yield improvement was driven more by coordinated nutrient uptake than by vegetative size alone, in line with reports that efficient N, P and K supply and strong nutrient-use efficiency are more important for yield in cereals than early vegetative vigour (Fageria *et al.*, 2014; Xia *et al.*, 2020; Khan *et al.*, 2023; Tan *et al.*, 2026).

4. Conclusions

The field experiment demonstrated that poultry manure and zinc application methods jointly influenced rice growth, productivity and nutrient uptake under the conditions of the Indo-Gangetic plain of West Bengal. Increasing poultry manure application generally improved crop responses to zinc fertilisation, although the magnitude of improvement differed among the application methods and measured parameters. The highest grain yield (6.59 t ha^{-1}) was obtained with 500 g m^{-2} poultry manure combined with basal application of zinc sulphate, representing a 70.28% increase over the control. In contrast, the combination of the same poultry manure rate with foliar zinc application produced the highest straw yield (6.18 t ha^{-1}) and zinc uptake (294.62 g ha^{-1}). Basal and foliar zinc application also favoured nitrogen, phosphorus and potassium uptake. Correlation analysis indicated stronger relationships between grain yield and nutrient uptake than between grain yield and individual vegetative traits. Principal component analysis further supported the close association between nutrient uptake and productivity. Overall, combining poultry manure with basal or foliar zinc application appears beneficial for improving rice productivity and nutrient acquisition within the experimental conditions. Further evaluation under different growing environments would help establish the consistency of these treatment responses.

5. Limitations

The experiment was conducted at a single location during one rabi season using the rice variety Satabdi. Consequently, the findings primarily represent the soil, climatic and crop-management conditions of the experimental site. Although the study assessed growth, yield attributes and nutrient uptake under different poultry manure and zinc treatments, the consistency of these responses across other rice varieties, soil conditions and growing seasons remains to be established. Further multi-location and multi-season field evaluations would help determine the broader applicability of the observed treatment responses.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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