



RESEARCH ARTICLE

Comparative responses of contrasting monsoon rice varieties to zinc feeding approaches under rainfed conditions

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Abstract

As a component of various biochemical and physiological processes, zinc (Zn) is an essential micronutrient for plants. Soil Zn deficiency has been very common worldwide especially in constantly wet soils of rice growing areas, leading to reduced rice yield reduction, reduced Zn content in rice grains and Zn malnutrition. Cultivation of Zn efficient rice varieties and using suitable Zn application approach is crucial to ensure Zn nutrition for rice. Therefore, a study was conducted following randomized complete block design (RCBD) design with three replications considering two contrasting monsoon rice varieties namely BRRI dhan34 (tall) and BRRI dhan49 (dwarf) and ten different Zn application approaches including control (no Zn application), soil application at 6 kg ZnSO₄ ha⁻¹, soil application at 8 kg ZnSO₄ ha⁻¹, soil application at 10 kg ZnSO₄ ha⁻¹, seedlings root dipping with 1.0 % ZnSO₄, seedlings root dipping with 1.5 % ZnSO₄, seedlings root dipping with 2.0 % ZnSO₄, Foliar spray with 1.0 % ZnSO₄, Foliar spray with 1.5 % ZnSO₄ and Foliar spray with 2.0 % ZnSO₄. Across the Zn application approaches, the average increase in plant height over control was recorded 6.59 % and 8.08 %, respectively for tall variety BRRI dhan34 and dwarf variety BRRI dhan49 and 5.77 % and 6.29 % increase in tiller number respectively for tall variety BRRI dhan34 and dwarf variety BRRI dhan49. The average increase in grain yield due to Zn application over control was recorded 9.84 % and 8.73 %, respectively for tall variety BRRI dhan34 and dwarf variety BRRI dhan49. Thus, tall variety was found more responsive to Zn application than the dwarf variety. Soil application appeared to be the best approach, as it resulted in a maximum 8.54 % increase in plant height, 9.31 % increase in tillering ability and 12.6 % increase in grain yield over no Zn application. Root dipping approach was found better than foliar spray only for increasing tillering ability, but foliar spray performed better than root dipping in increasing plant height and grain yield of monsoon rice.

Keywords

foliar spray; root dipping; soil application; zinc fertilization; zinc-use efficiency

Introduction

Zinc (Zn) deficiency is now common across the globe (around 30 % of world soil is Zn deficient) especially in the arid and semi-arid regions due to low Zn solubility and high Zn fixation resulting in significant yield losses in different crops (1). Zinc is an important micronutrient that plants take up as Zn²⁺ through the root system. Zinc is essential for various functions in plants viz. metabolism of carbohydrates, lipids, nucleic acid, auxin, enzyme activation and protein synthesis (2). But due to various reasons such as soil types (water-logged, saline or alkaline) lead to Zn deficiency in traditional cultivated land worldwide (3, 4). Frequent flooding and waterlogging in rice fields alter the soil pH, which influences Zn deficiency by reducing the amount of available Zn and promoting the formation of insoluble Zn compounds (5). Zinc deficient plants show symptoms including decreased leaf chlorophyll concentration, a reduced chlorophyll a:b ratio and reduced photosystem II efficacy (2). Thus, photosynthesis is impaired and overall yield is reduced. The rice plant can show about 20 % yield loss due to Zn deficiency (3).

Humans often consume Zn-deficient diets because rice, the major staple food, is frequently grown in soils with low Zn availability for plant uptake. Consequently, these populations face Zn deficiency and the symptoms include impaired growth, immunity, reproduction and brain development (3). The situation of Zn deficiency is worse in South and Southeast Asia where high proportion of cereal crops, such as rice and wheat, is consumed as a staple food (6). Approximately 17.3 % of the global population is at risk of inadequate Zn intake (7). In recent years, consumer demand for foods enriched with extra components, especially micronutrients that promote health and wellbeing beyond basic nutrition, has increased. Thus, Zn can be added to diet via biofortification, especially through Zn fertilization. The process is also simple and cost-effective (8).

Rice ranks as the second most important cereal crop globally, particularly in developing countries. Significant genotypic variation exists among rice varieties in terms of salt tolerance and Zn responsiveness (9). Differences among varieties in response to salt stress, Zn application and Zn accumulation are pronounced, making the identification of Zn-responsive varieties crucial for Zn biofortification strategies (10). Besides, application of Zn fertilizers enhances Zn uptake in diverse rice genotypes and improves crop yield (11). The improvement in rice grain yield at high Zn application may result from genotypic differences in Zn-related physiological processes, similar to the Zn-use efficiency variations observed in Mustard (12). The application of Zn enhances the average yield in hybrid rice (13).

Zinc is an expensive fertilizer; therefore, its application must be optimized to maximize efficiency and availability. Many researchers have carried out experiments to identify the most effective methods of Zn application for rice. Though soil application is most common, foliar spraying and root dipping have recently gained attention for their higher effectiveness and cost-efficiency (14, 15). According to previous studies, soil applied method was found most effective compared to foliar spray (16). Soil-applied Zn improves both grain yield and zinc content (17), whereas dipping seedlings in Zn solution enhances germination, root growth and shoot development (18). Foliar application also significantly increases zinc accumulation in rice grains (19). A study conducted in Pakistan found that applying zinc ethylenediaminetetraacetate (Zn-EDTA) to the soil 14 days after transplanting, along with recommended nitrogen, phosphorous and potassium (NPK) effectively corrected Zn deficiency and improved grain yield and nutrient content (20). It has also been reported that higher yields are obtained using methods such as nursery root dipping, foliar spraying and soil broadcasting of Zn (21). Similarly, it was observed that combining nitrogen with Zn significantly increased paddy yield and nutrient uptake compared to nitrogen alone (22).

Hence, selecting suitable zinc responsive variety and effective zinc application approach are crucial for both rice productivity and human nutrition, particularly in the region predominant with rice-based diets. The present study was therefore conducted to evaluate varietal responses of monsoon rice to zinc feeding and to identify the most suitable zinc application approach for higher rice productivity.

Materials and Methods

Experimental site and soil

The study was conducted at the Agronomy Field Laboratory (90°25'35.2" E and 24°43'07.3" N at an elevation of 18.5 m), Bangladesh Agricultural University, Mymensingh during the monsoon season (July-November) in 2023. The experimental soil belongs to the Sonatala soil series under the Old Brahmaputra Floodplain (AEZ-9). The land was medium-high with moderate drainage facilities. The soil was silty loam, nearly neutral in reaction (pH 6.58) and low in organic matter content (0.91 %). The experimental soil had a total nitrogen content of 0.72 %, available phosphorus of 15.98 ppm, exchangeable potassium of 0.22 meq per 100 g soil and available sulfur of 12.53 ppm. Soil zinc content was recorded 0.49 ppm which may be considered as very low (23). The study area has a subtropical climate. During the experimental period, the highest air temperature (33.8 °C) was recorded in June, while the lowest temperature (18.3 °C) was observed in November. The total rainfall during the experimental period was 1105.13 mm, the average relative humidity was 83.79 % and the average monthly sunshine duration was 185.36 hr.

Experimental treatments and design

Two experimental factors such as rice variety and Zn application approach were considered in the study. Two contrasting high yielding monsoon rice varieties include BRRI dhan34 (tall stature and fine grain) and BRRI dhan49 (dwarf stature and coarse grain). Ten Zn application approaches comprised i) No Zn application (control), ii) Soil application of ZnSO₄ at 6 kg ha⁻¹, iii) Soil application of ZnSO₄ at 8 kg ha⁻¹, iv) Soil application of ZnSO₄ at 10 kg ha⁻¹, v) Seedlings root dipping with 1.0 % ZnSO₄ solution, vi) Seedlings root dipping with 1.5 % ZnSO₄ solution, vii) Seedlings root dipping with 2.0 % ZnSO₄ solution, viii) Foliar spray with 1.0 % ZnSO₄ solution, ix) Foliar spray with 1.5 % ZnSO₄ solution, and x) Foliar spray with 2.0 % ZnSO₄ solution. In case of soil application, required amount of ZnSO₄ was applied and incorporated with soil before transplanting on seedlings. For the root dipping treatment, uprooted rice seedling roots were soaked in a ZnSO₄ solution (as per treatment) for 15 min before transplanting in the main field. In case of foliar spray, ZnSO₄ solution was prepared according to treatment and sprayed on the rice plants with a knapsack sprayer twice at 42 days after transplanting (DAT) (tillering stage) and at 72 DAT (booting stage). The experiment was laid out in a randomized complete block design (RCBD) with three replications. The total number of unit plots were 60. The size of each unit plot was 10 m² (4.0 m x 2.5 m). Block to block distance was 2 m and plot to plot distance was 1.0 m.

Crop husbandry

The land was opened on 30 July, 2023 and prepared by ploughing and cross ploughing with power tiller followed by laddering. The weeds, stubble and crop residues were removed from the plots. The land was fertilized with urea, triple superphosphate, muriate of potash and gypsum at the rate of 150, 100, 70 and 60 kg ha⁻¹, respectively as the source of nitrogen (N), phosphorous (P), potassium (K) and sulphur (S) for both the varieties. All the fertilizers and one third urea were applied at the time of final land preparation. Rest of the urea was applied in 2 equal splits at 30 and 50 DAT. Zinc as ZnSO₄ was applied as per treatment. 30 days old seedlings were

transplanted in the well-prepared puddled field on 3 August, 2023 at the rate of two seedlings hill⁻¹, maintaining line to line and plant to plant distance of 25 cm and 15 cm, respectively. Gap filling was done on 13 August, 2023 at 10 DAT where it was necessary. The crop was infested with some weeds such as durba grass (*Cynodon dactylon*), shama (*Echinochloa crusgalli*), panikachu (*Colocasia esculenta*) etc. which were controlled by manual weeding twice at 30 and 45 DAT. The crop was grown as rainfed due to sufficient rainfall in the monsoon season. In order to promote maturation, the field was drained out 10 days before harvest. There was no notable insect pest or disease infestation; consequently, no plant protection measures were taken.

Sampling, harvesting and data collection

Ten rice hills (excluding boundary hills) were randomly selected from each unit plot and marked to record plant height and tillering ability at regular intervals. Prior to harvest, those selected hills were separately collected to record data on various yield components. The date of harvesting was determined when 90 % of the grains became golden yellow in color. The grain yield was recorded by harvesting each plot independently. After harvesting, the crop was threshed, cleaned and dried to 14 % moisture content. The weight of grain was recorded and converted to t ha⁻¹.

Statistical analysis

All the data were compiled and tabulated in proper form for statistical analyses. Two-way analysis of variance (ANOVA) was done with the help of MSTAT-C computer package. The mean differences between treatments were tested with Duncan's multiple range test (DMRT) at 5 % level of probability. Duncan's multiple range test was used considering high number of treatments and to identify smaller differences between treatments as a powerful/liberal tool.

Results

Rice growth parameters

Growth of monsoon rice was measured in terms of plant height and tillering ability at regular intervals beginning from 30 DAT to harvest. Varietal effect on plant height of monsoon rice was significant at all

the sampling dates (Table 1). On the other hand, Zn application approach significantly affected plant height at 45, 60 DAT and at harvest, but not at early stage (30 DAT). Tall variety BRRI dhan34 produced taller plants than dwarf variety BRRI dhan49 at all the growth stages. At harvest, the height difference between the varieties was recorded 9 cm (Table 1).

A clear advantage of Zn application, irrespective of application approach on the plant height of monsoon rice was evident (Table 1). The maximum 10.52 % increase in plant height over control was recorded when ZnSO₄ was applied at 10 kg ha⁻¹ in soil compared to control (no Zn application). In general, rice plant height was found more responsive soil and foliar application of Zn than root dipping approach. Higher doses or concentration of Zn for any application approach resulted in higher plant height (Table 1).

Variety and Zn application approach interacted significantly to influence plant height of monsoon rice at all the sampling dates (Table 2). The maximum increase in plant height (over control) was recorded 8.33 %, 8.71 %, 8.85 % and 9.58 % respectively at 30, 45, 60 DAT and at harvest in BRRI dhan34 coupled with soil application of 10 kg ZnSO₄ ha⁻¹. At harvest, monsoon rice variety BRRI dhan34 gained > 10 cm higher height when fertilized with 10 kg ZnSO₄ ha⁻¹ as soil application compared to control. BRRI dhan49, on the other hand, attained 12 cm higher height than control when received 10 kg ZnSO₄ ha⁻¹ as soil application (Table 2).

Tillering ability of monsoon rice was significantly affected by variety at all the observations, but by Zn application approach only at harvest (Table 3). As observed for plant height, higher tillering ability was recorded in the tall variety BRRI dhan34 than in the dwarf variety, BRRI dhan49 from the early growth stage till harvest. BRRI dhan34 exhibited 14.26 %, 11.53 %, 13.09 % and 16.83 % higher tillering ability than BRRI dhan49 at 30, 45, 60 DAT and at harvest.

A clear influence of Zn application on increasing tillering ability of monsoon rice was evident from this study (Table 3). Increase in tillering ability due to Zn application over control ranged from 3.08 % to 10.95 %. Soil application of ZnSO₄ at 10 kg ha⁻¹ resulted in the highest tillering ability. In general, soil application of Zn performed better than root dipping and foliar spraying in term of

Table 1. Effect of variety and zinc application approach on plant height of monsoon rice

Variety	Plant height (cm) at different days after transplanting (DAT)			
	30 DAT	45 DAT	60 DAT	At harvest
BRRI dhan34	47.83a	94.12a	125.20a	128.67a
BRRI dhan49	43.09b	82.72b	105.71b	109.82b
Level of significance	**	**	**	**
Zinc application approach				
No zinc application (Control)	43.95	85.98b	109.52b	112.08b
Soil application of ZnSO ₄ at 6 kg ha ⁻¹	46.45	90.10ab	115.98ab	119.63ab
Soil application of ZnSO ₄ at 8 kg ha ⁻¹	47.93	91.68ab	117.27ab	121.18a
Soil application of ZnSO ₄ at 10 kg ha ⁻¹	47.95	93.40a	120.28a	123.87a
Seedling root dipping with 1.0 % ZnSO ₄	45.03	87.46ab	112.98ab	117.05ab
Seedling root dipping with 1.5 % ZnSO ₄	45.81	88.40ab	114.37ab	117.68ab
Seedling root dipping with 2.0 % ZnSO ₄	46.36	89.20ab	114.80ab	118.75ab
Foliar spray with 1.0 % ZnSO ₄	44.03	86.08b	114.98ab	119.37ab
Foliar spray with 1.5 % ZnSO ₄	43.50	85.71b	117.07ab	120.95a
Foliar spray with 2.0 % ZnSO ₄	43.58	86.20b	117.32ab	121.90a
Level of significance	NS	**	**	**
CV (%)	9.53	6.61	6.06	6.29

** =Significant at 1 % level of probability, NS = non-significant. In a column, figures having similar letter(s) or without letter(s) do not differ significantly whereas figures with dissimilar letter(s) differed significantly as per DMRT.

Table 2. Interaction effect of variety and zinc application approach on plant height of monsoon rice

Variety × Zn application approach		Plant height (cm) at different days after transplanting (DAT)			
		30 DAT	45 DAT	60 DAT	At harvest
BRRI dhan34	No zinc application (Control)	46.43a-d	91.43a-e	119.37ab	121.80a-c
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	48.76ab	95.43ab	125.37a	128.53a
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	50.16a	97.56a	127.13a	130.47a
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	50.30a	99.40a	129.93a	133.47a
	Seedling root dipping with 1.0 % ZnSO ₄	47.46a-d	93.20a-c	122.90a	126.43ab
	Seedling root dipping with 1.5 % ZnSO ₄	48.20a-c	94.46ab	124.30a	127.37a
	Seedling root dipping with 2.0 % ZnSO ₄	48.46a-c	95.36ab	124.70a	128.17a
	Foliar spray with 1.0 % ZnSO ₄	46.63ab-d	92.46a-d	124.67a	128.23a
	Foliar spray with 1.5 % ZnSO ₄	46.20a-d	90.80a-g	126.53a	130.73a
	Foliar spray with 2.0 % ZnSO ₄	45.66a-d	91.13a-f	127.13a	131.50a
BRRI dhan49	No zinc application (Control)	41.46cd	80.53h	99.67c	102.37d
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	44.13a-d	84.76c-h	106.60c	110.73cd
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	45.70a-d	85.80b-h	107.4c	111.90cd
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	45.60a-d	87.40b-h	110.63bc	114.27b-d
	Seedling root dipping with 1.0 % ZnSO ₄	42.60 b-d	81.73f-h	103.07c	107.67d
	Seedling root dipping with 1.5 % ZnSO ₄	43.43a-d	82.33e-h	104.43c	108.00d
	Seedling root dipping with 2.0 % ZnSO ₄	44.26a-d	83.03d-h	104.90c	109.33d
	Foliar spray with 1.0 % ZnSO ₄	41.43cd	79.70h	105.30c	110.50cd
	Foliar spray with 1.5 % ZnSO ₄	40.80d	80.63h	107.60c	111.17cd
	Foliar spray with 2.0 % ZnSO ₄	41.50cd	81.26gh	107.50c	112.30cd
Level of significance		**	**	**	**
CV (%)		9.53	6.61	6.06	6.29

** =Significant at 1 % level of probability. In a column, figures having similar letter(s) or without letter(s) do not differ significantly whereas figures with dissimilar letter(s) differed significantly as per DMRT.

Table 3. Effect of variety and zinc application approach on tillering ability of monsoon rice

Variety	Total tillers hill ⁻¹ at different days after transplanting (DAT)			
	30 DAT	45 DAT	60 DAT	At harvest
BRRI dhan34	8.09 a	15.47a	17.70 a	16.59 a
BRRI dhan49	7.08 b	13.87 b	15.65 b	14.20 b
Level of significance	**	**	**	**
Zinc application approach				
No zinc application (Control)	7.26	14.16	15.89	14.61b
Soil application of ZnSO ₄ at 6 kg ha ⁻¹	7.78	14.71	16.77	15.53ab
Soil application of ZnSO ₄ at 8 kg ha ⁻¹	7.98	15.35	17.46	16.15a
Soil application of ZnSO ₄ at 10 kg ha ⁻¹	8.02	15.39	17.52	16.21a
Seedling root dipping with 1.0 % ZnSO ₄	7.49	14.47	16.59	15.23ab
Seedling root dipping with 1.5 % ZnSO ₄	7.62	14.70	16.73	15.46ab
Seedling root dipping with 2.0 % ZnSO ₄	7.76	14.73	16.75	15.51ab
Foliar spray with 1.0 % ZnSO ₄	7.36	14.37	16.45	15.10ab
Foliar spray with 1.5 % ZnSO ₄	7.28	14.35	16.31	15.06ab
Foliar spray with 2.0 % ZnSO ₄	7.25	14.45	16.29	15.10ab
Level of significance	NS	NS	NS	**
CV (%)	14.63	15.95	14.08	8.38

** =Significant at 1 % level of probability, NS = non-significant. In a column, figures having similar letter(s) or without letter(s) do not differ significantly whereas figures with dissimilar letter(s) differed significantly as per DMRT.

tiller production.

Interaction effect between variety and Zn application approach exerted significant influence on tillering ability of monsoon rice only at early growth stage (30 DAT) and at harvest (Table 4). Tall variety BRRI dhan34 interacted favourably with Soil application of ZnSO₄ at 10 kg ha⁻¹ to show highest tillering ability at harvest. On the other hand, dwarf variety BRRI dhan49 coupled with no Zn application resulted in poorest tillering ability at harvest.

Rice yield parameters

All the yield parameters observed were significantly affected by variety and Zn application approach (Table 5). Tall variety BRRI dhan34 performed better than dwarf variety BRRI dhan49 in terms of effective tiller hill⁻¹ production (16.85 % higher) and grains panicle⁻¹ production (33.15 % higher). On the other hand, being a coarse grain variety BRRI dhan49 higher thousand grain weight (75.5 % higher)

than BRRI dhan34, a fine grain variety.

A positive influence of Zn application, irrespective of application approach, on all the yield parameters of monsoon rice is evident from (Table 5). For all the yield contributing parameters studied, soil application of ZnSO₄ at 10 kg ha⁻¹ produced the highest values which were 17.33 % (effective tiller hill⁻¹), 12.87 % (grains panicle⁻¹) and 10.22 % (thousand grain weight) higher than control (no zinc application). In general, soil application approach performed the best followed by root dipping and foliar spray for all the yield parameters.

Variety and Zinc application approach significantly interacted for all the yield parameters of monsoon rice (Table 6). Both the varieties produced the lowest values for all the yield parameters when no zinc was applied. Compared to no zinc application, BRRI dhan34 produced 17.39 % higher effective tiller hill⁻¹, 10.31 % higher grains

Table 4. Interaction effect of variety and zinc application approach on tillering ability of monsoon rice

Variety × Zn application approach		Total tillers hill ⁻¹ at different days after transplanting (DAT)			
		30 DAT	45 DAT	60 DAT	At harvest
BRRI dhan34	No zinc application (Control)	7.71ab	14.79	16.94	15.76a-f
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	8.26ab	15.42	17.75	16.61a-c
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	8.42ab	16.23	18.33	17.19ab
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	8.61a	16.21	18.69	17.54a
	Seedling root dipping with 1.0 % ZnSO ₄	8.08ab	15.47	17.64	16.53a-d
	Seedling root dipping with 1.5 % ZnSO ₄	8.10ab	15.43	17.70	16.59a-c
	Seedling root dipping with 2.0 % ZnSO ₄	8.21ab	15.41	17.77	16.63a-c
	Foliar spray with 1.0 % ZnSO ₄	7.93ab	15.30	17.51	16.40a-e
	Foliar spray with 1.5 % ZnSO ₄	7.84ab	15.07	17.36	16.34a-e
	Foliar spray with 2.0 % ZnSO ₄	7.75ab	15.38	17.37	16.29a-e
BRRI dhan49	No zinc application (Control)	6.82ab	13.54	14.85	13.46g
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	7.31ab	14.00	15.79	14.45d-g
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	7.55ab	14.48	16.59	15.10b-g
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	7.45ab	14.58	16.35	14.89c-g
	Seedling root dipping with 1.0 % ZnSO ₄	6.92ab	13.48	15.53	13.93fg
	Seedling root dipping with 1.5 % ZnSO ₄	7.14ab	13.97	15.76	14.33e-g
	Seedling root dipping with 2.0 % ZnSO ₄	7.32ab	14.05	15.74	14.39e-g
	Foliar spray with 1.0 % ZnSO ₄	6.80ab	13.43	15.39	13.80fg
	Foliar spray with 1.5 % ZnSO ₄	6.73b	13.64	15.26	13.77fg
	Foliar spray with 2.0 % ZnSO ₄	6.76b	13.53	15.22	13.91fg
Level of significance		**	NS	NS	**
CV (%)		14.63	15.95	14.08	8.38

** = Significant at 1 % level of probability, NS = non-significant. In a column, figures having similar letter(s) or without letter(s) do not differ significantly whereas figures with dissimilar letter(s) differed significantly as per DMRT.

Table 5. Effect of variety and zinc application approach on yield contributing characters and yield of monsoon rice

Variety	Effective tillers hill ⁻¹	Grains panicle ⁻¹	1000-grain weight (g)	Grain yield (t ha ⁻¹)
BRRI dhan34	15.25a	128.68a	11.67b	3.55b
BRRI dhan49	13.05b	96.64b	20.49a	3.69a
Level of significance	**	**	**	**
Zinc application approach				
No zinc application (Control)	12.98b	104.47f	15.16c	3.34f
Soil application of ZnSO ₄ at 6 kg ha ⁻¹	14.21ab	113.78c	16.15a-c	3.64cd
Soil application of ZnSO ₄ at 8 kg ha ⁻¹	14.93a	116.95ab	16.45ab	3.75b
Soil application of ZnSO ₄ at 10 kg ha ⁻¹	15.23a	117.92a	16.71a	3.89a
Seedling root dipping with 1.0 % ZnSO ₄	13.90ab	107.95e	15.60bc	3.48e
Seedling root dipping with 1.5 % ZnSO ₄	14.17ab	110.12d	15.88a-c	3.54e
Seedling root dipping with 2.0 % ZnSO ₄	14.26ab	110.72d	16.01a-c	3.54e
Foliar spray with 1.0 % ZnSO ₄	13.93ab	113.13c	16.11a-c	3.63d
Foliar spray with 1.5 % ZnSO ₄	13.99ab	115.73b	16.28ab	3.66cd
Foliar spray with 2.0 % ZnSO ₄	13.92ab	115.87b	16.46ab	3.71bc
Level of significance	**	**	**	**
CV (%)	9.90	1.45	5.45	1.86

** = Significant at 1 % level of probability. In a column, figures having similar letter(s) or without letter(s) do not differ significantly. whereas figures with dissimilar letter(s) differed significantly as per DMRT.

panicle⁻¹ and 14.95 % higher thousand grain weight when received ZnSO₄ at 10 kg ha⁻¹ as soil application. BRRI dhan34, on the other hand, produced 17.51 % higher effective tiller hill⁻¹, 16.43 % higher grains panicle⁻¹ and 7.64 % higher thousand grain weight when received ZnSO₄ at 10 kg ha⁻¹ as soil application compared to control.

Rice yield

A significant influence of variety and Zn application approach on the grain yield of monsoon rice was recorded (Table 5). Dwarf variety BRRI dhan49 out yielded tall variety BRRI dhan34 with a yield advantage of 3.95 %. Despite lower number of effective tillers and grain number, higher yield of BRRI dhan49 was the outcome of heavier grains compared to BRRI dhan34.

Due to application Zn fertilizer, increase in grain yield of monsoon rice ranged from 4.19 % to 16.46 % over control. Soil application of ZnSO₄ at 10 kg ha⁻¹ appeared as the best approach for grain yield of monsoon rice. Root dipping with 1 % ZnSO₄ resulted in the lowest grain yield after control treatment. In general, soil application was the most productive approach followed by foliar

spray and root dipping for monsoon rice yield (Table 5).

Rice variety and Zn application approach interacted significantly to influence the grain yield of monsoon rice (Table 6). Irrespective of variety, no zinc application (control) resulted in the lowest grain yield. Dwarf variety BRRI dhan49 coupled with soil application ZnSO₄ at 10 kg ha⁻¹ produced the highest grain yield which was 15.8 % higher than respective control. On the other hand, tall variety BRRI dhan34 coupled with soil application ZnSO₄ at 10 kg ha⁻¹ produced the highest grain yield which was 17.7 % higher than respective control. In general, both the varieties produced the highest grain yield when zinc was applied to soil, while root dipping approach performed the worst (Table 6).

Comparative responses of variety

Comparative response of variety to zinc application approach in terms of plant height (at harvest) has been presented in (Fig. 1). The highest and lowest increase in plant height over control of BRRI dhan34 were recorded 9.58 % and 6.1 % in case of soil application of ZnSO₄ at 10 kg ha⁻¹ and root dipping with 2% ZnSO₄, respectively. On

Table 6. Interaction effects of variety and zinc application approach on yield contributing characters and yield of monsoon rice

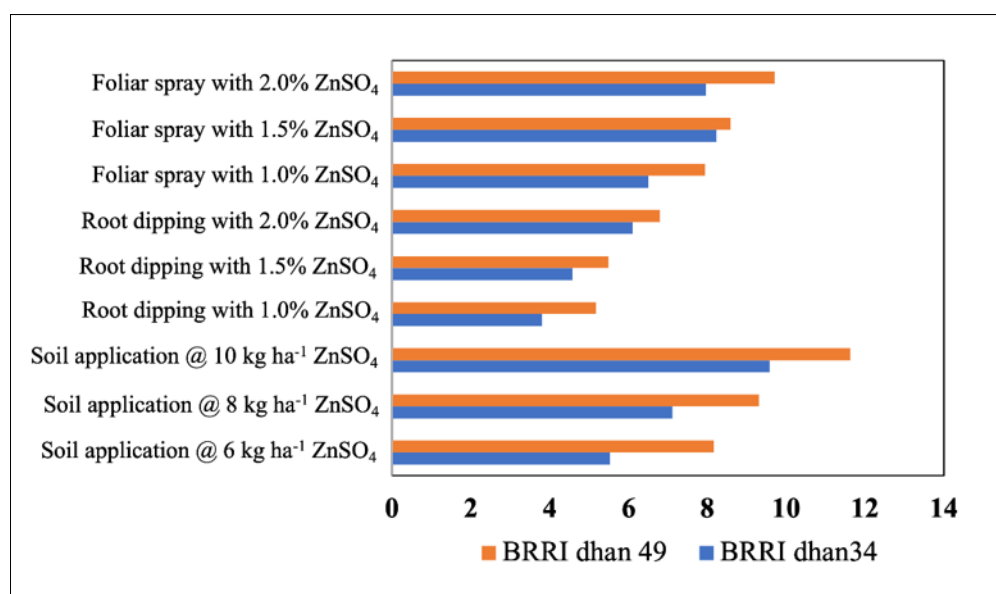
Variety × Zn application approach		Effective tillers hill ⁻¹	Grains panicle ⁻¹	1000-grain weight (g)	Grain yield (t ha ⁻¹)
BRRI dhan34	No zinc application (Control)	14.03b-f	121.2h	10.70d	3.26i
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	15.28a-c	129.7c-e	12.00cd	3.66c-e
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	15.86ab	132.4ab	12.06cd	3.68cd
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	16.47a	133.7a	12.30c	3.82b
	Seedling root dipping with 1.0 % ZnSO ₄	15.17a-c	124.7g	11.33cd	3.46gh
	Seedling root dipping with 1.5 % ZnSO ₄	15.26a-c	126.4fg	11.5 cd	3.46gh
	Seedling root dipping with 2.0 % ZnSO ₄	15.23a-c	127.2e-g	11.5 cd	3.43h
	Foliar spray with 1.0 % ZnSO ₄	15.07a-e	128.8d-f	11.70cd	3.54fg
	Foliar spray with 1.5 % ZnSO ₄	15.14a-d	131.6a-c	11.76cd	3.56e-g
	Foliar spray with 2.0 % ZnSO ₄	15.06a-e	130.8b-d	11.83cd	3.62d-f
BRRI dhan49	No zinc application (Control)	11.93 f	87.62m	19.63b	3.42h
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	13.15c-f	97.81j	20.30ab	3.62d-f
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	14.00b-f	101.44i	20.83ab	3.82b
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	14.02b-f	102.02i	21.13a	3.96a
	Seedling root dipping with 1.0 % ZnSO ₄	12.63f	91.17l	19.86ab	3.50gh
	Seedling root dipping with 1.5 % ZnSO ₄	13.09c-f	93.80kl	20.26ab	3.63d-f
	Seedling root dipping with 2.0 % ZnSO ₄	13.29c-f	94.21k	20.46ab	3.66c-e
	Foliar spray with 1.0 % ZnSO ₄	12.80ef	97.48j	20.53ab	3.72b-d
	Foliar spray with 1.5 % ZnSO ₄	12.84d-f	99.81ij	20.80ab	3.75bc
	Foliar spray with 2.0 % ZnSO ₄	12.78ef	100.8i	21.10a	3.81b
Level of significance		**	**	**	*
CV (%)		9.90	1.45	5.45	1.86

** = Significant at 1 % level of probability. In a column, figures having similar letter(s) or without letter(s) do not differ significantly. whereas figures with dissimilar letter(s) differed significantly as per DMRT.

the other hand, BRRI dhan49 attained the maximum 11.62 % height increase over control when received ZnSO₄ at 10 kg ha⁻¹ as soil application and the minimum 5.49 % increase in plant height over control when seedlings were root dipped in 1.5 % ZnSO₄ (Fig. 1). Comparative response of variety to Zn application approach in terms of tillering ability (at harvest) has been presented in (Fig. 2). The highest and lowest increase in tiller number over control of BRRI dhan34 were recorded 11.29 % and 3.38 % in case of soil application of ZnSO₄ at 10 kg ha⁻¹ and foliar spray with 2 % ZnSO₄, respectively. On the other hand, BRRI dhan49 attained the maximum 12.18 % tiller number increase over control when received ZnSO₄ at 8 kg ha⁻¹ as soil application and the minimum 3.29 % increase in tillering ability over control when foliar sprayed with 1.5 % ZnSO₄ (Fig. 2). Comparative response of variety to zinc application approach in terms of grain yield has been presented in (Fig. 3). The highest and lowest increase in grain yield over control of BRRI dhan34 were

recorded 17.17 % and 5.21 % in case of soil application of ZnSO₄ at 10 kg ha⁻¹ and root dipping with 2 % ZnSO₄, respectively. On the other hand, BRRI dhan49 attained the maximum 15.78 % grain yield increase over control when received ZnSO₄ at 10 kg ha⁻¹ as soil application and the minimum 2.33 % increase in grain yield over control when seedlings were root dipped in 1.0 % ZnSO₄ (Fig. 3).

The comparative growth and yield responses of monsoon rice varieties to Zn application have been summarized in (Fig. 4). Across the Zn application approaches, the average increase in plant height due to Zn application over control was recorded 6.59 % and 8.08 %, respectively for tall variety BRRI dhan34 and dwarf variety BRRI dhan49. It indicates that dwarf variety was more responsive to Zn application than tall variety. The average increase in tiller number due to Zn application over control was recorded 5.77 % and 6.29 %, respectively for tall variety BRRI dhan34 and dwarf variety BRRI

**Fig. 1.** Varietal comparison of plant height increase (%) over control under different zinc application approaches.

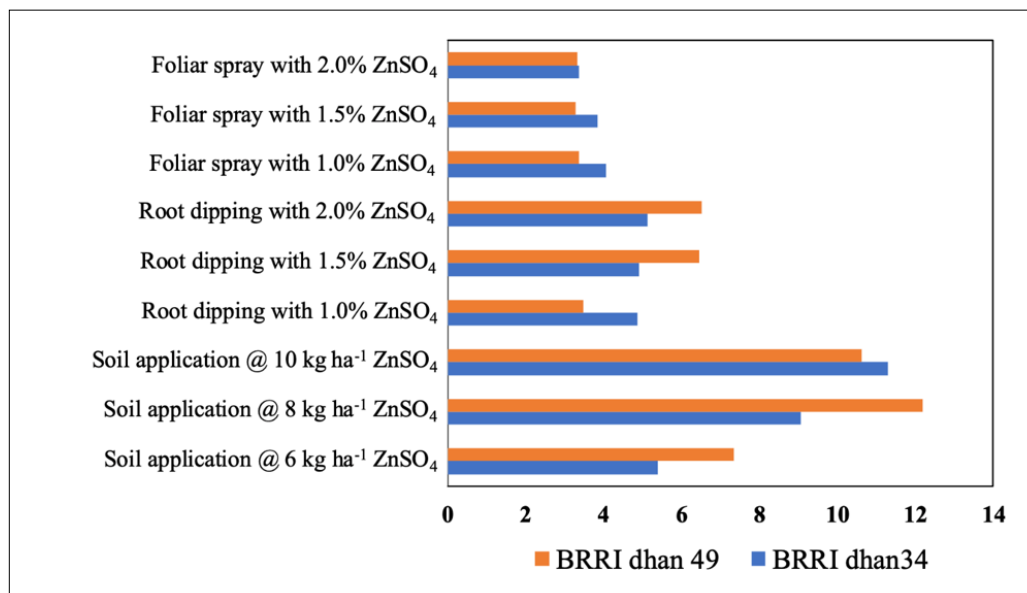


Fig. 2. Varietal comparison of tillering ability increase (%) over control under different zinc application approaches.

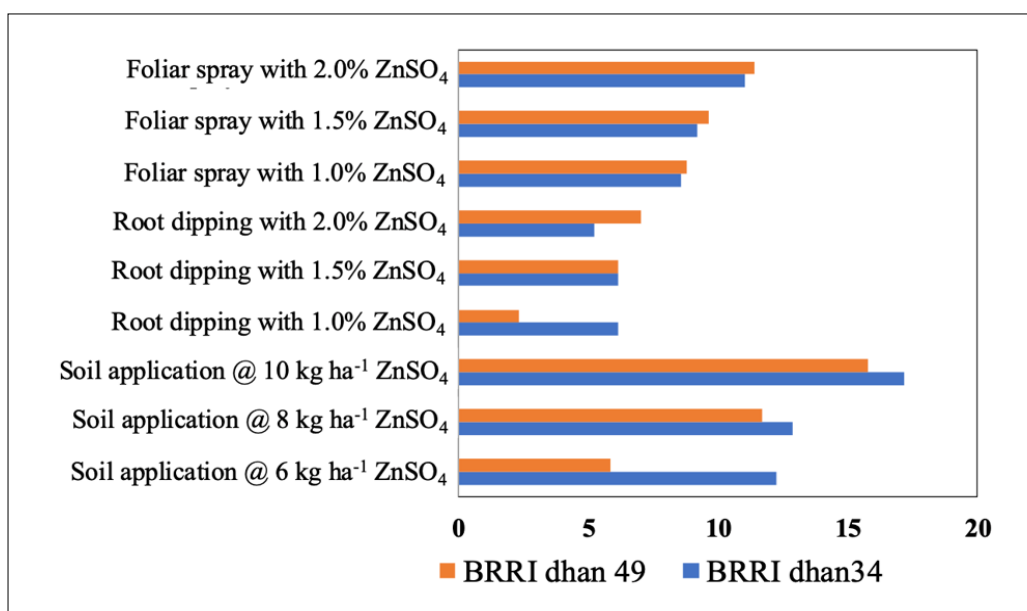


Fig. 3. Varietal comparison of grain yield increase (%) over control under different zinc application approaches.

dhan49 indicating more responsiveness of dwarf variety to Zn application than tall variety. Across the Zn application approaches, the average increase in grain yields due to Zn application over control was recorded 9.84 % and 8.73 %, respectively for tall variety BRRi dhan34 and dwarf variety BRRi dhan49. Unlike growth parameters, tall variety BRRi dhan34 was found more responsive to Zn application than the dwarf variety BRRi dhan49 (Fig. 4).

Comparative performances of zinc application approaches

The comparative performances of different Zn application approaches (across the Zn rate/concentration and varieties) in terms of growth and yield responses of monsoon rice have been summarized in (Fig. 5). Soil application appeared as the best approach as it resulted in the highest 8.54 % increase in plant height, 9.31 % increase in tillering ability and 12.6 % increase in grain yield over no Zn application. Root dipping approach was found better than foliar spray only for increasing tillering ability of monsoon rice (5.23 % and 3.54 % increase over control, respectively). Foliar spray, on the other hand performed better than root dipping in increasing plant height (8.15 % and 5.32 % increase over control, respectively) and grain yield of monsoon rice (9.77 % and 5.49 % increase over

control, respectively).

Economics of Zinc application approach

The findings indicate that Zn fertilization remarkably improves economic returns compared to control treatments for both varieties. Specifically, BRRi dhan34 showed the highest gross and net returns when treated with ZnSO₄ at 10 kg ha⁻¹ as soil application. In contrast, the control treatment, which involved no Zn application, yielded the lowest returns. Moreover, the most favourable benefit-cost ratio (2.11) was observed when BRRi dhan34 was treated with ZnSO₄ at 10 kg ha⁻¹ as soil application, suggesting that this level of Zn fertilization is optimal for maximizing profitability. Lowest benefit-cost ratio (1.30) was recorded when BRRi dhan49 was treated with ZnSO₄ at 1 % as seedling root dipping and under control. Overall, BRRi dhan34 was found to be more financially rewarding than the BRRi dhan49, highlighting its potential for better economic outcomes in Zn-fertilized conditions (Table 7).

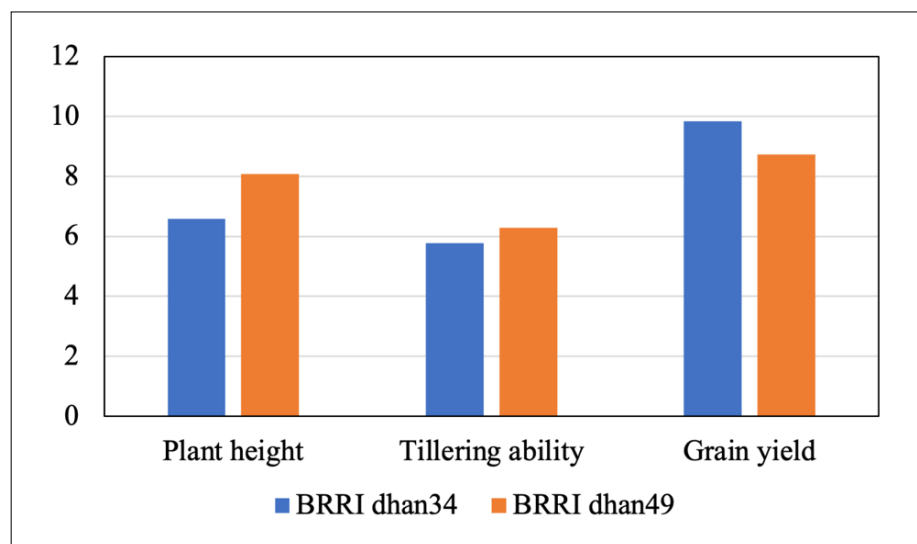


Fig. 4. Comparative growth and yield response of monsoon rice varieties across the zinc application approaches.

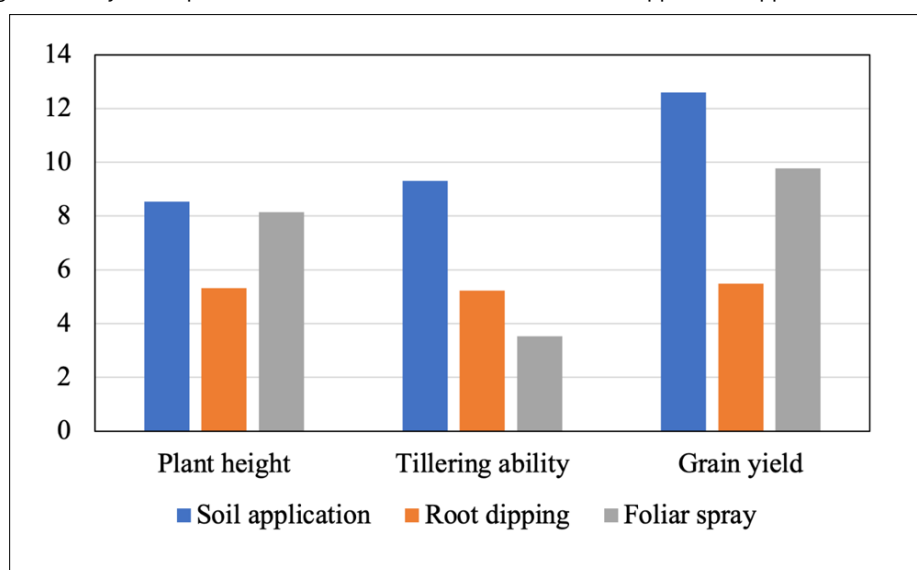


Fig. 5. Comparative growth and yield response of zinc application approaches across the monsoon rice varieties.

Table 7. Economics of different zinc application approaches of two monsoon rice varieties

Variety × Zn application approach		Total variable cost (BDT ha ⁻¹)	Gross return (BDT ha ⁻¹)	Net return (BDT ha ⁻¹)	Benefit: Cost (BCR)
BRRI dhan34	No zinc application (Control)	121900	225520	103620	1.85
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	123950	252480	128530	2.04
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	124450	254000	129550	2.04
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	124950	264000	139050	2.11
	Seedling root dipping with 1.0 % ZnSO ₄	124250	239840	115590	1.93
	Seedling root dipping with 1.5 % ZnSO ₄	124875	240640	115765	1.93
	Seedling root dipping with 2.0 % ZnSO ₄	125500	239400	113900	1.91
	Foliar spray with 1.0 % ZnSO ₄	127250	245120	117870	1.93
	Foliar spray with 1.5 % ZnSO ₄	128325	247280	118955	1.93
	Foliar spray with 2.0 % ZnSO ₄	129300	251120	121820	1.94
BRRI dhan49	No zinc application (Control)	116900	151460	34560	1.30
	Soil application of ZnSO ₄ at 6 kg ha ⁻¹	118950	160300	41350	1.35
	Soil application of ZnSO ₄ at 8 kg ha ⁻¹	119450	168500	49050	1.41
	Soil application of ZnSO ₄ at 10 kg ha ⁻¹	119950	174760	54810	1.46
	Seedling root dipping with 1.0 % ZnSO ₄	119250	155460	36210	1.30
	Seedling root dipping with 1.5 % ZnSO ₄	119875	160970	41095	1.34
	Seedling root dipping with 2.0 % ZnSO ₄	120500	162500	42000	1.35
	Foliar spray with 1.0 % ZnSO ₄	120050	164280	42030	1.34
	Foliar spray with 1.5 % ZnSO ₄	121675	166050	42725	1.35
	Foliar spray with 2.0 % ZnSO ₄	123200	168710	44410	1.36

1 US\$ = 121 BDT (Bangladeshi Taka)

Discussion

In this experiment, the growth and yield characteristics of two distinct rice genotypes were assessed in relation to external Zn fertilizer treatment through soil, seedling root dipping and foliar application. Different rice varieties react differently to Zn depending on the dosage and mode of application. It was also observed that the plant height and tillering ability of both varieties increased with Zn application, with soil-applied ZnSO_4 having the biggest impact. However, the dwarf variety, BRRI dhan49, responded more strongly to various Zn applications in terms of height and tillering than the tall variety, BRRI dhan34. Under the same Zn treatments, dwarf varieties outperformed taller varieties in terms of growth characteristics, suggesting that Zn uptake varies depending on genotype. These differences are consistent with previous results suggesting that the efficiency of Zn consumption, absorption and translocation may vary among types (24–26). The dwarf variety's receptive nature to a sufficient Zn supply may hasten enzyme activity and auxin metabolism, which in turn may boost crop development. In contrast to growth parameters, it was discovered that the tall variety responded better to Zn application than the dwarf variety when grain yield was taken into account. In this study, the tall variety, BRRI dhan34, exhibited a higher grain yield response despite showing a comparatively lower vegetative growth response than the dwarf variety, BRRI dhan49. This variation may be attributed to genotypic differences in yield responsiveness, Zn uptake and utilization efficiency, tolerance to Zn deficiency, sink capacity and dry matter partitioning efficiency between the two varieties. Greater sink strength, including a higher spikelet-bearing capacity, may have enabled the tall genotype to utilize Zn-enhanced photosynthates more effectively for grain formation. However, detailed morpho-physiological investigations are required to elucidate the underlying mechanisms responsible for these varietal differences. This can be accounted for by biomass partitioning and sink capacity. The differences across cultivars and their reactions to Zn fertilizer highlight the potential significance of plant genetic resources in nutrient management and environmental adaptation techniques.

This experiment demonstrated a definite benefit of Zn application, regardless of application method, on monsoon rice growth and yield. Increasing the Zn supply to rice has a positive impact on tiller production and raised the overall Zn content per plant at various growth stages (27, 28). According to studies, treatments that include higher Zn concentrations resulted in higher grain and straw yields (29). It is impossible to overstate the significance of Zn in controlling a number of biological and physiological processes in plants. Because Zn is involved in over 300 plant enzyme activities, a Zn deficit will restrict rice output and growth (22). Auxin control, protein synthesis, pollen generation, carbohydrate metabolism and cell turgidity maintenance are all impacted by these enzymes (22).

Zinc is also necessary for the regulation of gene expression associated with stress defense responses in plants; as a result, plants lacking Zn are more vulnerable to damage from fungal pathogen invasion, excessive light and severe temperatures (30, 31). Additionally, Zn shortage in rice lowers pollen viability, which results in less grain set and significant yield penalties (32). Therefore, applying is essential to reach rice's potential development and output. However, for plants to use Zn efficiently, the right application technique at the right time in a suitable manner is more important (33).

Although soil application is the most widely used method for applying zinc, foliar application and root dipping have lately gained popularity due to their increased effectiveness and affordability (14, 15). Several Zn treatment techniques, including foliar spraying, seedling root dipping and soil application, were used in this experiment in varying dosages. When compared to other Zn applications, soil application seemed to be the most effective strategy since it increased plant height, tillering ability and grain yield. Higher Zn input is possible with soil application, which also provides residual availability in soils that do not fix Zn well and aids in the establishment of a long-term nutrient reservoir (34). In soil, Zn can be found in a variety of forms, such as chelated, exchangeable, organically adsorbed, water-soluble and solution Zn. Because of high carbonates, bicarbonates, pH levels, phosphorus content and imbalances in macronutrient fertilizers, plants mainly obtain Zn from the soil as Zn^{2+} , ZnOH^+ or Zn complexes with soluble organic materials (35, 36). In addition to these, studies also found that Zn applied to the soil increased rice grain yield more than foliar spray did (33). It is further observed that Zn applied to the soil performed better than foliar spray and root dipping (16). Additionally, from this study it was discovered that the root dipping method was superior than foliar spraying alone in terms of improving monsoon rice's capacity to tiller. In contrast, foliar spray outperformed root dipping in terms of raising monsoon rice plant height and grain output. In our study, soil application of Zn out yielded foliar spray and root dipping methods. This was due to the fact that soil application confirms a consistent supply of Zn throughout the growing period. Moreover, unlike foliar spray soil application is less affected drift loss and rain washing off allowing sufficient uptake of Zn. Although, there are risks of Zn fixation and immobilization making Zn unavailable to roots. Foliar spray Zn performed better than root dipping in terms of rice yield. The possible reason behind is foliar spray serves as a concentrated booster confirming up to 90 % uptake and utilization of Zn by leaf stomata and epidermis providing direct and faster action that results in higher grain yield and Zn bio fortification. In case of root dipping, on the other hand, the absorption rate of Zn by roots is much lower especially when seedling roots are got damaged during uprooting from the nursery bed immediately followed by root dipping. It may not be essential to provide extra Zn if the rice seedlings absorb enough of it before transplanting; thus, the roots of the rice seedlings may be treated with Zn solution prior to transplanting. Conversely, Zn foliar treatment is acknowledged as a successful strategy for promptly addressing deficits and increasing productivity (37). The benefits of foliar spray include reducing losses from leaching and fixing, controlling plant nutrient absorption and facilitating quick and efficient nutrient usage. Foliar nutrition is thought to be a crucial method of fertilizing at the right periods of growth since the nutrients can readily pass through the leaf cuticles and enhance crop utilization. However, foliar spray is more efficient in rapidly raising the Zn content in the grain, whereas soil application offers more substantial and long-term advantages, such as raising crop output (38). Zinc is an expensive fertilizer; thus, its application must optimize its availability and effectiveness. In this experiment, soil application was found to be the most effective technique of applying Zn in terms of plant development and overall production. Considering the cost related issue, soil application was also more acceptable than other methods. Therefore, using Zn properly necessitates the appropriate method and dosage. A number of growth characteristics and yield-related factors can be enhanced by administering Zn in the right quantity and under the right circumstances.

Conclusion

Rice varietal responses to zinc (Zn) feeding were found to be variable in this study. Across the Zn application approaches, dwarf variety BRRI dhan49 responded better than tall variety BRRI dhan34 in terms of plant height and tillering ability. However, the average increase in grain yield due to Zn application over control was recorded higher (9.84 %) in tall variety BRRI dhan34 than dwarf variety BRRI dhan49 (8.73 %). Thus, tall variety was found more responsive to zinc application than the dwarf variety in terms of productivity. Zinc feeding approaches also had influence on rice growth and yield performance. Soil application appeared as the best approach as it resulted in the highest 8.54 % increase in plant height, 9.31 % increase in tillering ability and 12.6 % increase in grain yield over no Zn application. Root dipping approach was found better than foliar spray only for increasing tillering ability, but foliar spray performed better than root dipping in increasing plant height and grain yield of monsoon rice. Therefore, under the experimental conditions of this study, soil application of ZnSO₄ at 10 kg ha⁻¹ can be considered as best Zn feeding approach for superior growth and higher yield performance in rice.

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Authors' contributions

Conceptualization was carried out by MAP and FA. Methodology was developed by MAP and FA. Validation was performed by MAP, FA, SY and AKMMI. Formal analysis was conducted by MTR and MAP. Investigation was undertaken by MTR. Data curation was completed by MAP, MTR and FA. Writing—original draft preparation was carried out by MAP and MTR. Writing—review and editing were performed by AKMMI, SY, AK, SAK and MSHS. Visualization was done by MTR and AKMMI. Supervision was provided by MAP and FA. All authors read and approved the final version of the 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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