PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.2400

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RESEARCH ARTICLE

Improving grain yield and quality by enhancing accumulation of zinc in rice under subtropical condition

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OPEN ACCESS

ARTICLE HISTORY

Received: 31 January 2023
Accepted: 21 April 2023

Available online
Version 1.0 : 30 August 2023

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS,UGC Care etc. See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE

Jahan U A, Kheya S A, Sarker U K, Kaysar M S, Sumon M H, Chaki A K, Uddin M R. Improving grain yield and quality by enhancing accumulation of zinc in rice under subtropical condition. Plant Science Today (Early Access). https://doi.org/10.14719/pst.2400

Abstract

One of the primary abiotic factors limiting rice production is zinc (Zn) deficiency. Effective management of Zn in rice soils is crucial, as rice is a staple crop for many nations. To address this issue, a pot trial was conducted at the net house of the Department of Agronomy, Bangladesh Agricultural University, Mymensingh, from December 2019 to May 2020. The trail aimed to assess the impact of zinc on yield performance and grain zinc content of rice. The experiment employed a completely randomized design (CRD) with three replications, involving the applications of 6 different rates of Zn to 3 distinct varieties of *boro* rice. The result revealed that BRRI dhan28 exhibited superior yield and yield-related traits when treated with 12 kg Zn ha^{-1}. Meanwhile, the application of 10 kg Zn ha^{-1} resulted in the highest Zn content in the grain of BRRI dhan74, considering the quantity of Zn accumulated by the grain. Based on the findings of the study, it can be concluded that applying 12 kg of Zn ha^{-1} is likely the optimal Zn management strategy to achieve outstanding performance in the rice cultivar BRRI dhan28. Furthermore, applying 10 kg of Zn ha^{-1} may enhance the Zn content of the grain in BRRI dhan74.

Keywords

Zinc, biofortification, *boro* rice, productivity, malnutrition

Introduction

Rice stands out as one of the world's most widely cultivated grains, constituting a substantial share of cereal consumption and production (1). Remarkably, over 50% of the global population depends on rice as a staple food (2). In the realm of nutrition, food security and economics, no other cereal grain holds greater importance than rice. However, ensuring food security in the face of a burgeoning global population presents a formidable challenge (3). Consequently, the development of novel strategies and techniques will play a pivotal role in shaping the future of rice production (4). However, as rice cultivation takes place in an increasingly precarious environment, it faces additional challenges, including nutritional deficiencies, moisture stress, pests and diseases infections, as well as weed infestations, all of which hinder its growth and diminish production. With the rising utilization of macronutrient (NPK) fertilizers and the widespread cultivation of high-yielding rice varieties in recent years, several secondary micronutrients have been rapidly depleted from the soil, leading to shortages of these vital elements in various regions of the country

(5).Micronutrient malnutrition is a global concern, and in recent years, regions practicing intensive agriculture is practiced have begun to prioritize addressing its deficiencies. Inadequate intake or deficiency of essential micronutrients disrupt plant growth by interfering with metabolic and biochemical processes, ultimately leading to reduced yield and quality (6). Significantly, malnutrition is a prevalent issue, particularly in impoverished nations like Bangladesh, where people consume primarily starchy staple foods that lacks essential micronutrients (7). Among micronutrient deficits, zinc insufficiency stands out as one of the most critical agricultural challenges worldwide. Despite being a vital microelement, the widespread shortage of zinc in both plants and human diets is cause for alarm (8, 9). Due to the diverse physiological and biochemical functions that Zn serves in plants, even a minor deficiency can have detrimental effects on development, production and the Zn content in plant parts used for food. Zinc deficiency predominantly impact nations where cereals constitute a fundamental component of the diet, posing a humanitarian concern, particularly in regions where cultivation occurs in Zn-deficient soils (10-12). Consequently, there has been a suggestion that increasing the Zn content in staple foods such as rice could potentially contribute to alleviating Zn deficiency (5). Numerous rice-growing regions world-wide have reported prevalent zinc inadequacy in their rice crops (13). In the early stages of development, insufficient Zn availability leads to leaf bronzing and a reduced number of tillers ,consequently retarding maturity and decreasing rice yield (14). Addressing Zn deficiency in rice through methods like fortification (adding Zn to food products during processing) or supplementation is neither cost-effective nor a sustainable long-term solutions (15). However, biofortification presents a pragmatic and economical approach to enhance the bioavailability of zinc in the edible parts of plants and mitigate zinc nutritional deficits (16, 17). The fact that rice lacks essential micronutrients like Zn underscores the critical importance of biofortification for this staple crop. Zinc biofortification in food crops can be achieved through either a genetic approach or agronomic method such as appropriate soil and plant fertilizer application (8). Agronomic biofortification refers to the deliberate use of mineral fertilizers to increase the content of a specific mineral in the edible part of crops, thereby enhancing the intake of the desired nutrient (18). This practice is also referred to as ferti-fortification (19). Agronomic biofortification enhances crops's ability to utilize and mobilize micronutrients, thereby promoting crop growth (9). To biofortify cereals with Zn, maintaining a sufficient quantity of available Zn in soil is essential. However, while higher zinc fertilizer rates may increase Zn uptake, this approach might not be cost-effective as cultivation expenses rise. Zn fertilization not only elevates the nutritional value of these products for humans but also augments production and grain Zn content in cereal crops (20). Another strategy to improve Zn accessibility for plants in lowland environments involves selection of suitable Zn sources for soil application (21). The commonly utilized Zn source is $ZnSO_4$, valued for its high dissolution rate and affordability. Additionally, Zn-EDTA (ethylene diamine tetra acetic acid) is recommended due to its effectiveness in enhancing Zn availability for the plant (7). Nonetheless, among various approaches to address Zn deficiency, Zn biofortification, aimed at increasing Zn content in rice grains, emerges as the most practical, enduring, and economical solution. While a majority of Zn fertilizer experiments and subsequent recommendations for rice have focused on rectifying fertilizer Zn insufficiency, there have been relatively few studies on enhancing zinc accumulation in rice through Zn application.

Given the preceding information, the current study aimed to assess the importance of zinc fertilization in augmenting zinc accumulation in rice grains.

Materials and Methods

Features of experimental location

The investigation took place at the net house of the Department of Agronomy, Bangladesh Agricultural University, Mymensingh, using 30 Litre pots with a diameter of 35 cm and filled with 25 kg soil. The study location is situated at latitude 24°42′55′′N, longitude 90°25′ 47′′E, and elevation 19m above sea level. The test location is within the Old Brahmaputra floodplain (AEZ-9) (22) and experiences a subtropical monsoon climate with a humid environment. Prior to the experiment, composite topsoil samples (0-20 cm) were collected from the field for analysis. The physiochemical constituents of the soil that were analysed are presented in Table 1.

Table 1. Physiochemical properties of the soil in the field before starting the experiment

Soil Property	Values
Soil texture	Clay loam
Soil colour	Dark grey
Soil pH	6.13
Eelectric conductivity (µs/cm)	648
Organic carbon (%)	1.274
Total nitrogen (%)	0.112
Available form of phosphorus (P) (ppm)	28.2
Available form of potassium (K) (ppm)	83.64
Available form of sulphur (S) (ppm)	25.90

Experimental set up

The experimental treatment consisted of two components: six different rates of zinc viz., 0 kg ha^{-1} (Zn_0), 8 kg ha^{-1} (Zn_8), 10 kg ha^{-1}(Zn_{10}), 12 kg ha^{-1} (Zn_{12}), 14 kg ha^{-1} (Zn_{14}), 16 kg ha^{-1} (Zn_{16}), applied on 3 distinct *boro* rice varieties namely, BRRI dhan64, BRRI dhan74 and BRRI dhan28. Zn was applied as $ZnSO_4$ and doses were converted from kg ha^{-1} to g pot^{-1}. With a total of 54(9×6) pots and 9(3×3) pots in each batch, the experiment was replicated 3 times using a completely randomized design (CRD). In each replication, nine pots were positioned next to each other with a distance of 10 to 25 cm in between them. Table 2 provides the evaluation % of the cultivars, along with some of their key qualities, in order to assess their adaptability to different attributes.

Table 2. Parental line and significant characters of the rice cultivars tested in the experiment

Name of cultivar	Parentage	Duration (days)	Ecosystem	Salient features	Recommended for cultivation
BRRI dhan64	IR75382-32-2-3-3× BR7166-4-5-3-2-5-5b1-92	152	Irrigated	Very high yield potential and medium slender grain, zinc rich, yield: 7.0 t/ha	All Bangladesh
BRRI dhan74	IR68144×BRRI dhan29	145	Irrigated	Very high yield potential and medium slender grain, zinc rich, no lodging, yield: 8.0 t/ha	All Bangladesh
BRRI dhan28	BR6(IR28) × Purbachi	140	Irrigated lowland	Early maturing and medium slender grain, yield: 6.0 t/ha	Sylhet, Netrakona belt (flash flood area)

Preparation of pot and crop husbandry

Pots were placed within the net house, each containing 25 kg of dry soil, and sufficient water was added to attain an appropriate soil moisture level. Fertilizers, including urea, triple super phosphate (TSP), muriate of potash (MoP), and gypsum, were applied at rates of 1.5g, 0.75g, 0.95g and 0.45g per pot respectively. Zinc sulphate (ZnSO4) was applied according to the specifications for each treatment. During the final pot preparation, all fertilizers except for urea were administered in full doses. Urea was divided into 3 equal portions and applied at 15-, 30- and 50- day intervals following transplantation. On January 12, 2020, seedlings specific to each cultivar, nurtured for forty days in a nursery bed, were transplanted into the pots containing 4cm of water. Additional water was supplied as needed after the initial ponded water subsided. Pond irrigation continued until 15 days before harvest. Weeds were occasionally observed during the growth period, particularly in the early stages and were manually removed. No significant insect infestations were noted during the growth phase, except for rice hispa which was managed by applying pesticides (Fenitrothion 50 EC) at the tillering stage.

Harvesting and data collection

Upon reaching maturity (90% ripened grain), the entire plant was cut at the ground level using a sickle. Each pot's harvested crop was packed and carefully marked separately. After sun drying of the plant materials,detailed records were made for yield contributing parameters, as well as for grain and straw yields.

Chemical analysis

Rice grains harvested from 5 plants pot^{-1} were thoroughly dried in oven at 65 °C. After dehusking, the dried grain samples were finely powdered using a ball mill. In a desiccator, the powdered grain was stored in zip-log polythene bags. Zn concentrations were determined by analyzing the grain powders**.** 200 mg of rice powder was precisely measured using a Mettler Toledo Analytical Balance, and placed into labelled digestion containers (a Velp block digester). Each digestion tube received 5 cc of nitric acid (70% RCI Premium Labscan). Nitric acid in the same volume was added to the tubes labelled as Certified Reference Material and Blanks (NMIJ CRM7501-a, Japan). Tubes were left overnight for pre digestion. Following the pre-digestion period, 2ml of 30% hydrogen peroxide was added to each vessel via pipette. Tubes were then left open for 15 minutes for outgassing. Subsequently, the vessels were placed in the block digester, and the temperature was gradually raised to 140 ˚C. A dense straw brown fume was developed inside the vessels. The digestion continued for 5 hrs until a clean white fume was visible. Finally, the block digester was switched off and left for cooling. The digested material was transferred into 50 mL centrifuge tube, ensuring the complete transfer by washing the digestion vessel with deionized water. Final volume was made adjusted to 50 mL using deionized water and the weight was recorded again to calculate dilution factor (w/w). The digested samples were subsequently analysed using an Atomic Absorption Spectrometer (AAS) at the Soil Resource Development Institute (SRDI) lab, Jamalpur to determine zinc concentration in rice grains. Finally, the rice grain zinc concentrations were reported in mg kg^{-1}.

Statistical analysis

The data recorded for various parameters were properly collated, tabulated and statistically analyzed. The analysis of variance was carried out using the MSTAT-C software tool. Duncan's Multiple Range Test was used to adjudge the mean differences between the treatments (23).

Results

ANOVA of experimental factors

Table 3 presents the analysis of variances for yield and yield-contributing features. All the parameters were significantly influenced by the varietal effect. Except for PH (plant height), Zn fertilizer had a notable impact on all the parameters. The interaction between variety and Zn rate exerted a considerable impact on nearly all parameters, although it did not significantly affect the TGW (1000-grain weight). Variety also had a significant effect on the zinc content of rice grain. Additionally, Zn fertilization significantly influenced the Zn content of rice grain. Moreover, the interaction between variety and Zn fertilization demonstrated a substantial impact on Zn concentration in the rice grain.

Varietal effect on yield and yield related traits

Significant differences were observed among the rice varieties in terms of yield and yield related traits. A range of PH among the 3 rice cultivars was assessed to between 88.16 cm to 105.13 cm . Notably, BRRI dhan28 exhibited the tallest plant, while BRRI dhan64 produced the shortest. BRRI dhan28 also recorded the highest no. of TT (total tillers hill^{-1}) (8.25) and ET (effective tillers hill^{-1}) (7.73), whereas BRRI dhan64 displayed the lowest TT (5.67) and ET (5.12). Similarly, the highest PL (panicle length) (30.52 cm) was observed in the BRRI dhan28 variety, while the shortest (27.47 cm) was found in BRRI dhan64. Likewise, BRRI

Table 3. Analysis of variance of the data for yield and yield contributing parameters

Source of variation	PH (cm)	TT (no.)	ET (no.)	PL (cm)	GP (no.)	TGW (g)	GY (g pot^{-1})	SY (g pot^{-1})	BY (g pot^{-1})	HI (%)	Zn content in rice grain (mg kg^{-1})
Variety (V)	**	**	**	**	**	**	**	**	**	**	**
Zn Level (Zn)	NS	**	**	**	**	**	**	**	**	**	**
Variety × Zn Level (V×Zn)	**	**	**	**	**	NS	**	**	**	**	**

** =Significant at 1% level of probability, NS = Not significant, Here, PH= Plant height, TT=Total tillers hill^{-1}, Et= Effective tillers hill^{-1}, PL= Panicle length, GP= grains panicle^{-1}, TGW= 1000-grain weight, GY= Grain yield, SY= Straw yield, BY= Biological yield, HI= Harvest index

dhan28 exhibited the highest no. of GP (grains panicle^{-1}) (241.77) whereas BRRI dhan64 had the lowest GP (195.31). Among the varieties, BRRI dhan28 attained the highest weight (23.01 g), while BRRI dhan64 had the lowest weight (21.23 g). The result indicated that BRRI dhan28 produced the highest GY (grain yield) (30.77 g pot^{-1}), SY (straw yield) (45.05 g pot^{-1}), and BY (biological yield) (75.83 g pot^{-1}). Conversely, BRRI dhan64 yielded the lowest GY (26.46 g pot^{-1}), SY (42.28 g pot^{-1}), and BY (68.74 g pot^{-1}).The HI (harvest index) of three rice varieties ranged from 38.44% to 40.52%, with BRRI dhan28 having the highest and BRRI dhan64 the lowest (Table 4).

Zn fertilizer level's effect on yield and yield related traits

Significant differences in the yield and yield-related traits of rice were observed due to varying Zn fertilizer rates. Tiller production increased by 2.49% to 16.35% as a result of Zn fertilization compared to the control, where tiller number increased from 6.42 to 7.47 due to Zn fertilization. An increasing trend in the TT was noted up to 12 kg Zn ha^{-1}, followed by a declining trend. The trial results indicate that the ET count ranged from 5.84 to 6.95, with a 19.00% increase due to the application of 12 kg Zn ha^{-1}. In contrast, only a 1.88% increase in ET was observed with Zn_{16} treatment. The highest PL of 31.10 cm was achieved with Zn_{12} treatment, while the shortest, 25.55 cm, was recorded for Zn_{16} treatment. The number of GP ranged from 177.96 to 265.81, with Zn_{12} treatment yielding the most and Zn_0 providing the least. A substantial 49.36% increase in GP count was observed with the application of 12 kg Zn ha^{-1} compared to the control.

TGW varied between 21.05 g and 23.02 g, with the highest weight associated with Zn_{12} treatment, and the lowest with Zn_{10}. GY significantly ranged between 25.68 g pot^{-1} and 31.23 g pot^{-1}, with a linear increase observed as zinc doses were increased up to 12 kg ha^{-1}. The maximum GY was achieved with Zn_{12} treatment, while Zn_0 resulted in the lowest. Zn fertilization led to a 3.93% to 21.61% increase in grain yield compared to the control. Similarly, Zn_{12} treatment yielded the highest straw yield (SY) of 45.81 g pot^{-1}, representing a 10.87% increase compared to the control's 41.32 g pot^{-1}. Biomass yield (BY) increased by 3.71% to 14.98% due to Zn fertilization, with the highest BY of 77.04 g pot^{-1} observed in Zn_{12} treatment, and the lowest of 67.00 g pot^{-1} from Zn_0. Zn fertilization also contributed to a 4.08% to 13.35% increase in HI. The highest HI of 41.69% was recorded with Zn_{12}, while the lowest of 36.78% was obtained from Zn_0 (Table 5).

Interaction effect of variety and Zn fertilizer rate on yield and yield related traits

With the exception of TGW, the interaction between variety and Zn fertilizer levels exerted a significant impact on yield and yield-contributing traits. Notable variations in PH were observed, with BRRI dhan28 treated with 12 kg Zn ha^{-1} reaching the tallest height (106.11 cm), while BRRI dhan64 without Zn application exhibited the shortest height (87.33 cm). Similarly, the highest number of tillers (TT) (9.22) was achieved through the interaction of BRRI dhan28 with Zn_{12}, representing a 23.92% increase compared to the control. Conversely, the lowest tiller count (5.10) was recorded for BRRI dhan64 with no Zn application. The number of effective tillers (ET) ranged from 4.44 to 8.88, with BRRI dhan28 and Zn_{12} resulting in the highest count and BRRI dhan64 with Zn_0 yielding the lowest. A significant increase of approximately 21.25% in panicle length (PL) was observed in BRRI dhan28 when treated with 12 kg Zn ha^{-1}, accompanied by the longest panicle (35.15 cm), whereas the combination of BRRI dhan74 and Zn_{14} resulted in the shortest panicle (22.10 cm). The number of grains per panicle (GP) ranged from 133.88 to 274.11, with the highest count associated with BRRI dhan28 and Zn_{12}, and the

Table 4. Effect of variety on yield and yield contributing parameters of rice

Variety	PH (cm)	TT (no.)	ET (no.)	PL (cm)	GP (no.)	TGW (g)	GY (g pot^{-1})	SY (g pot^{-1})	BY (g pot^{-1})	HI (%)
BRRI dhan64	88.16c*	5.67c	5.12c	27.47c	195.31c	21.23c	26.46b	42.28c	68.74c	38.44b
BRRI dhan74	89.24b	6.69b	6.21b	28.38b	220.50b	22.16b	27.60b	43.63b	71.23b	38.69b
BRRI dhan28	105.13a	8.25a	7.73a	30.52a	241.77a	23.01a	30.77a	45.05a	75.83a	40.52a
LSD $_{(0.05)}$	0.64	0.18	0.21	0.85	3.65	0.32	1.23	0.74	1.45	1.12

*In a column, figures with the same letter (s) or without letter do not differ significantly whereas figures with dissimilar letters differ significantly (as per DMRT).
Here, PH= Plant height, TT=Total tillers hill^{-1}, Et= Effective tillers hill^{-1}, PL= Panicle length, GP= Grains panicle^{-1}, TGW= 1000-grain weight, GY= Grain yield, SY= Straw yield, BY= Biological yield, HI= Harvest index

Table 5. Effect of Zn fertilizer on yield and yield contributing parameters

Zn fertilizer level	PH (cm)	TT (no.)	ET (no.)	PL (cm)	GP (no.)	TGW (g)	GY (g pot^{-1})	SY (g pot^{-1})	BY (g pot^{-1})	HI (%)
0 kg ha^{-1}	93.84*	6.42c	5.84c	28.36b	177.96e	22.13bc	25.68e	41.32c	67.00e	36.78c
8 kg Zn ha^{-1}	94.10	6.77b	6.36b	30.85a	191.44d	22.75a	28.74bc	43.50b	72.24c	39.75b
10 kg Zn ha^{-1}	94.25	7.35a	6.73a	30.40a	208.14c	21.05d	29.54ab	44.79a	74.33b	38.28bc
12 kg Zn ha^{-1}	94.66	7.47a	6.95a	31.10a	265.81a	23.02a	31.23a	45.81a	77.04a	41.69a
14 kg Zn ha^{-1}	93.92	6.81b	6.30b	26.47c	236.92b	22.19b	27.76cd	43.59b	71.35c	39.19b
16 kg Zn ha^{-1}	94.25	6.58bc	5.95c	25.55c	234.88b	21.68c	26.69de	42.90b	69.49d	39.62b
LSD $_{(0.05)}$	0.91	0.27	0.30	1.20	5.16	0.45	1.74	1.05	2.06	1.58

*In a column, figures with the same letter (s) or without letter do not differ significantly whereas figures with dissimilar letter differ significantly (as per DMRT),Here, PH= Plant height, TT=Total tillers hill^{-1}, Et= Effective tillers hill^{-1}, PL= Panicle length, TGW= 1000-grain weight, GY= Grain yield, SY= Straw yield, BY= Biological yield, HI= Harvest index

lowest with BRRI dhan74 and Zn_0 (Table 6). Zn fertilization led to an increase of up to 26.63% in grain yield (GY) across rice varieties compared to the control. GY ranged from 24.82 g pot^{-1} to 33.57g pot^{-1}, with the highest recorded in BRRI dhan28 with Zn_{12} and the lowest in BRRI dhan64 with Zn_0. Similarly, the treatment combination of BRRI dhan28 with Zn_{12} yielded the highest straw yield (SY) (46.19 g pot^{-1}), while the lowest SY (40.57 g pot^{-1}) was seen in BRRI dhan64 with Zn_0. Statistically, the highest biomass yield (BY) (79.76 g pot^{-1}) was achieved in BRRI dhan28 with Zn_{12}, and the lowest (65.39g pot^{-1}) in BRRI dhan64 with Zn_0. Harvest index (HI) varied from 36.37% to 42.08% across different varieties and zinc levels. Among the combinations, BRRI dhan28 with Zn_{12} exhibited the highest HI, while the lowest HI was found in BRRI dhan64 with Zn_0 (Table 7).

Zn accumulation

The zinc quantity present in rice grains was notably influenced by variety. Zn content in rice grains ranged from 25.53 mg kg^{-1} to 37.25 mg kg^{-1}, with the highest value observed in BRRI dhan74, which was statistically equivalent to BRRI dhan64, while the lowest value was recorded in BRRI dhan28 (Fig. 1). Zn accumulation in rice grains exhibited significant variations due to Zn fertilization. In comparison to the control, Zn fertilization led to a substantial increase in Zn accumulation, ranging from 16.39% to 42.76%. Specifically, Zn content in rice grains rose from 27.20 mg kg^{-1} in the control treatment to 38.83 mg kg^{-1} by Zn fertilization. An increase in Zn accumulation was observed up to 10 kg Zn ha^{-1}, but further increases in Zn dose resulted in diminished accumulation. Notably, Zn content saw a 42.76% increase with the application of Zn_{10}, while only 16.39% increase was recorded with Zn_{16}(Fig. 2). The interaction between varieties and Zn fertilization was found to significantly influence Zn content in rice grain. Compared to the control treatment, the application of Zn fertilizer substantially raised Zn content in rice grains of different varieties by 5.00% to 45.79%. The finding revealed that the combination of BRRI dhan74 with Zn_{10} yielded the highest Zn content (45.22 mg kg^{-1}) compared to other interactions. In contrast, BRRI dhan28 with Zn_0 exhibited poor Zn accumulation performance, registering the lowest Zn content (21.38 mg kg^{-1}) with this combination (Fig. 3).

Table 6. Interaction effect of variety and Zn levels on plant characters and yield contributing parameters of rice

Variety	Zn fertilizer level	PH (cm)	TT (no.)	ET (no.)	PL (cm)	GP (no.)
BRRI dhan64	0 kg ha^{-1}	87.33e*	5.10h	4.44k	23.55i	206.44f
	8 kg Zn ha^{-1}	88.78cde	5.21h	4.55jk	30.21cd	163.33i
	10 kg Zn ha^{-1}	88.55cde	6.88e	6.10fg	30.33cd	177.66h
	12 kg Zn ha^{-1}	88.33cde	6.55e	5.11i	26.99fg	217.11e
	14 kg Zn ha^{-1}	104.11b	5.88f	5.44hi	24.10hi	239.11d
	16 kg Zn ha^{-1}	105.66ab	6.55e	6.11fg	27.08fg	257.22bc
BRRI dhan74	0 kg ha^{-1}	89.33cd	7.55d	7.10cd	29.99cd	133.88j
	8 kg Zn ha^{-1}	88.44cde	5.32gh	4.99ij	32.66b	173.88h
	10 kg Zn ha^{-1}	104.55ab	7.88cd	7.55bc	26.10gh	221.22e
	12 kg Zn ha^{-1}	89.55c	8.10bc	7.66b	31.66bc	235.66d
	14 kg Zn ha^{-1}	89.22cd	6.44e	5.77gh	22.10i	203.22f
	16 kg Zn ha^{-1}	89.22cd	7.44d	6.88de	30.33cd	266.11ab
BRRI dhan28	0 kg ha^{-1}	104.88ab	7.44d	6.66de	28.99def	193.55g
	8 kg Zn ha^{-1}	89.33cd	8.44b	7.99b	30.44cd	225.55e
	10 kg Zn ha^{-1}	105.44ab	8.44b	7.88b	29.22de	237.11d
	12 kg Zn ha^{-1}	106.11a	9.22a	8.88a	35.15a	274.11a
	14 kg Zn ha^{-1}	88.44cde	5.77fg	5.11i	31.77bc	268.44a
	16 kg Zn ha^{-1}	87.89de	5.55fgh	5.11i	27.55efg	251.88c
LSD $_{(0.05)}$		1.57	0.46	0.53	2.08	8.94

*In a column, figures with the same letter (s) or without letter do not differ significantly whereas figures with dissimilar letter differ significantly (as per DMRT),
Here, PH= Plant height, TT=Total tillers hill^{-1}, ET= Effective tillers hill^{-1}, PL= Panicle length, GP= grains panicle^{-1}

Table 7. Interaction effect of variety and Zn levels on yield and yield contributing parameters of rice

Variety	Zn fertilizer level	TGW (g)	GY (g pot^{-1})	SY (g pot^{-1})	BY (g pot^{-1})	HI (%)
BRRI dhan64	0 kg ha^{-1}	22.35*	24.82h	40.57h	65.39f	36.37e
	8 kg Zn ha^{-1}	22.6	26.51e-h	41.11h	67.62ef	39.18bcd
	10 kg Zn ha^{-1}	20.31	25.12gh	42.21fgh	67.33ef	37.26cde
	12 kg Zn ha^{-1}	21.15	25.53gh	41.65gh	67.18ef	38.79b-e
	14 kg Zn ha^{-1}	22.22	25.91fgh	42.32fgh	68.23ef	37.97cde
	16 kg Zn ha^{-1}	19.26	31.43ab	43.28efg	74.72c	42.04a
BRRI dhan74	0 kg ha^{-1}	23.13	24.87h	43.48def	68.35ef	36.89de
	8 kg Zn ha^{-1}	22.27	27.11d-h	44.88b-e	71.99d	39.19bcd
	10 kg Zn ha^{-1}	23.41	30.79abc	41.17h	71.96d	37.92cde
	12 kg Zn ha^{-1}	22.33	29.53bcd	46.57ab	76.11bc	37.98cde
	14 kg Zn ha^{-1}	22.73	25.73gh	41.17h	66.91f	38.45b-e
	16 kg Zn ha^{-1}	22.2	28.87b-f	41.91fgh	70.79de	40.77ab
BRRI dhan28	0 kg ha^{-1}	20.9	28.12c-g	46.17abc	74.29c	37.09cde
	8 kg Zn ha^{-1}	19.83	27.09d-h	44.51cde	71.06d	40.88ab
	10 kg Zn ha^{-1}	23.02	28.94b-e	46.17abc	75.21bc	39.67abc
	12 kg Zn ha^{-1}	24.10	33.57a	46.19a	79.76a	42.08a
	14 kg Zn ha^{-1}	23.08	31.65ab	45.21bcd	76.86abc	41.14ab
	16 kg Zn ha^{-1}	23.58	33.37a	45.58bc	78.95ab	42.07a
CV%		2.14	6.44	2.50	2.99	4.22

*In a column, figures with the same letter (s) or without letter do not differ significantly whereas figures with dissimilar letter differ significantly (as per DMRT)

Here, TGW= 1000-grain weight, GY= Grain yield, SY= Straw yield, BY= Biological yield, HI= Harvest index

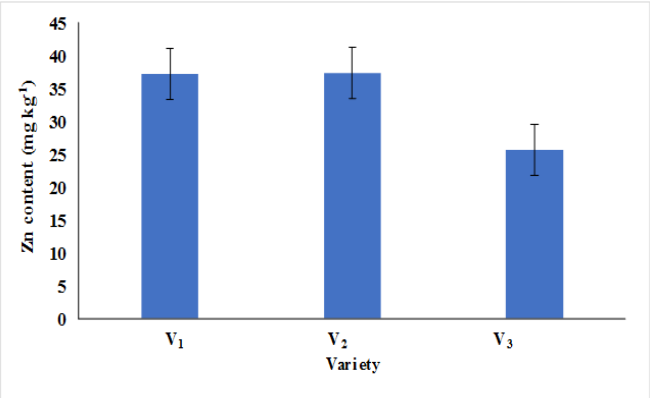

Fig. 1. Zn accumulation in grain as influenced by variety.
Here,V_1 = BRRI dhan64, V_2 = BRRI dhan74, V_3 = BRRI dhan28

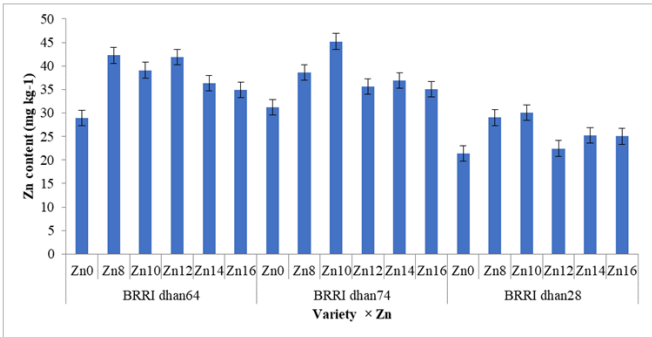

Fig. 3. Zn accumulation in grain as influenced by variety and Zn fertilizer.
Here, Zn_0= 0 kg ha^{-1}, Zn_8= 8 kg ha^{-1}, Zn_{10}= 10 kg ha^{-1}, Zn_{12}= 12 kg ha^{-1}, Zn_{14}= 14 kg ha^{-1}, Zn_{16}= 16 kg ha^{-1}

Discussion

Insufficient Zn supply or unfavourable soil conditions can hinder plant growth by limiting Zn uptake. Zn fertilization is vital agricultural practice for rice plants, and studies have demonstrated its impact on rice's Zn absorption capacity (24). The optimization of Zn levels is essential to achieve increased yield and higher Zn concentration in rice grains.

The experimental finding indicates that cultivars

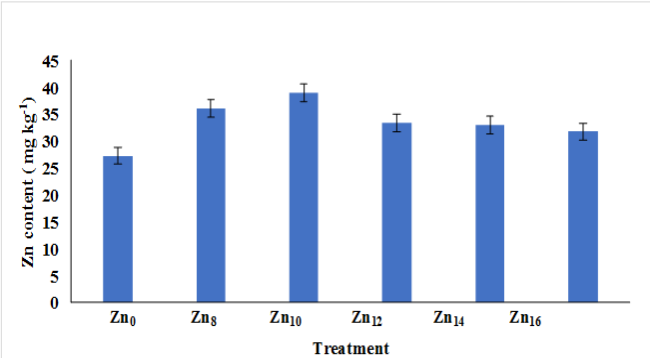

Fig. 2. Zn accumulation in grain as influenced by Zn fertilizer.
Here, Zn_0= 0 kg ha^{-1}, Zn_8= 8 kg ha^{-1}, Zn_{10}= 10 kg ha^{-1}, Zn_{12}= 12 kg ha^{-1}, Zn_{14}= 14 kg ha^{-1}, Zn_{16}= 16 kg ha^{-1}

exhibited varying performance across different Zn rates, with these differences being linked to yield and yield related characteristics. BRRI dhan28, in comparison to BRRI dhan64 and BRRI dhan74, demonstrated superior performance. The performance of a crop's variety is primarily influenced by its genetic makeup. This conclusion is supported by several studies (25-27).

Zinc fertilizer aims to enhance plant Zn absorption and elevate grain Zn content. Our current investigation demonstrates that the treatment of 12 kg Zn ha^{-1} yielded the highest values across all attributes, while the absence of zinc application yielded the lowest. This can likely be attributed to an ample supply of zinc, which may have improved the availability and absorption of other essential minerals, consequently enhancing crop performance. In contrast to the zero zinc treatment, it was observed that zinc concentrations of 1% and 2% significantly increased the height of rice plants (28). Numerous studies have shown that applying zinc to rice plants enhances traits such as TT, ET and GP (29-31). In this experiment, an initial increase in GY was observed up to 12 kg ha^{-1} Zn, followed by a decline with higher Zn rates, indicating that excessive Zn rates did not confer additional benefits in terms of GY.

While the 12 kg Zn ha^{-1} treatment resulted in the highest rice yield, it did not substantially differ from the 10 kg Zn ha^{-1} treatment. The crop's positive response to zinc application suggests that 12kg Zn ha^{-1} may be the optimal quantity for rice crops, as diminishing trend was observed beyond this point. Zn is essential, but an excess can be detrimental to plants by generating excessive reactive oxygen species (ROS), leading to oxidative damage (32). Using Zn fertilizer has been documented to potentially increase rice grain production by approximately 0.3%-13.0% up to a certain zinc level (33). The control group exhibited a lower rice yield, likely due to zinc deficiency, whereas the higher rice yield resulting from zinc application could be attributed to a synergy of yield-related factors, including ET, GP and WTG. The rise in chlorophyll content, leading to improved photosynthesis, the production of growth-promoting-compounds, metabolites, and enhanced plant development, may contribute to the increased productivity due to Zn fertilization (34). Zn treatment consistently promoted photosynthate translocation, contributing to higher GY and SY (35). Similarly, when BRRI dhan28 was treated with 12kg Zn ha^{-1}, this combination outperformed others in terms of PH, number of TT and ET, PL, number of GP, GY, SY, BY and HI. However, the lowest readings came from BRRI dhan64 with 0 kg Zn ha^{-1}. Conversely, the lowest readings were recorded for BRRI dhan64 with 0kg Zn ha^{-1}. The interaction between zinc fertilizer and rice variety was found to significantly affect the number of GP and GY (36, 37).

The results of the trial regarding the Zn accumulation in rice grains reveal that BRRI dhan74 exhibited the highest Zn accumulation in its grains compared to other varieties. Additionally, the application of 10 kg Zn ha^{-1} contributed to an elevated grain Zn content. Similarly, the combination of BRRI dhan74 and 10 kg Zn ha^{-1} demonstrated the highest zinc content in rice grains. In contrast, while the cultivar BRRI dhan28 displayed a higher grain yield than BRRI dhan74, the Zn concentration in both rice varieties showed an inverse trend. This discrepancy might be attributed to the greater potential of BRRI dhan74 to translocate Zn to its reproductive part under the influence of 10kg Zn ha^{-1}. Previous research has indicated that soil application of 10kg Zn ha^{-1} enhanced rice grain Zn content and bioavailability (38). Furthermore, a pot experiment demonstrated that a gradual rise in Zn levels up to 15mg Zn kg^{-1} soil led to a significant enhancement in Zn content in brown rice (39).

Conclusion

In conclusion, BRRI dhan28 treated with 12 kg ha^{-1} of Zn demonstrated the most favorable outcomes in terms of yield and yield-related traits, while BRRI dhan74 with 10 kg ha^{-1} Zn, exhibited the highest Zn accumulation. To optimize both zinc content in the rice variety and achieve a satisfactory yield, this study recommends the application of zinc fertilizer at a rate of 12 kg ha^{-1}.

Acknowledgements

This research was supported by Ministry of Science and Technology (MOST), Government of the Peoples' Republic of Bangladesh. So the authors are thankful to Ministry of Science and Technology (MOST), Bangladesh for providing the grant.

Authors' contributions

UAJ carried out the experiment, participated in data collection and drafted the manuscript. SAK was involved in data collection and review of literature. MSK performed the statistical analysis. UKS, MHS, AKC and MRU reviewed and edited the manuscript. 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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