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RESEARCH ARTICLE

Integrated Zinc and Boron Fertilization Enhances Growth and Yield of Fine Rice (cv. Binadhan-25)

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ABSTRACT

Micronutrient deficiencies, particularly zinc (Zn) and boron (B), are widespread in the rice-growing regions of Bangladesh, posing a significant barrier to achieving optimal crop productivity. To address this issue, a field experiment was conducted during the *Boro* season at the Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh, to assess the effects of integrated use of Zn and B on the growth and yield performance of fine rice variety Binadhan-25. The study comprised eleven treatments involving different combinations of basal and foliar applications of Zn and B. It was laid out in a Randomized Complete Block Design (RCBD) with three replications. Among the treatments, the combined application of 50% Zn and B as basal and 50% as foliar spray showed superior results in terms of plant height (114.66 cm), number of effective tillers hill^{-1} (9.89), grain yield (6.98 t ha^{-1}), straw yield (7.42 t ha^{-1}), 1000-grain weight (21.88 g), biological yield (14.40 t ha^{-1}), and harvest index (48.46%). These results were significantly higher than those recorded in the control plots, which showed the poorest performance across most parameters. The findings suggest that integrated application of Zn and B, both as basal and foliar spray, in combination with recommended NPK fertilization, can effectively overcome micronutrient deficiencies and improve rice growth and productivity, offering a practical solution for sustainable rice production.

Keywords: *Micronutrients, Rice productivity, Agronomic Yield*

INTRODUCTION

Rice (*Oryza sativa* L.) is a staple cereal crop and primary food source in Bangladesh, cultivated in 78% of the country's total cropped area (Hasan *et al.,* 2025; Roy *et al*., 2024; Jahan *et al.,* 2017). Bangladesh ranks 3rd among the countries that cultivate rice in terms of production (Mamun *et al.,* 2021). Rice is grown on over 11.7 million hectares in Bangladesh and produced 20,768 metric tons of Boro rice in the year 2023-2024 (BBS, 2024). With the population growing by approximately 2 million people each year, the total population is projected to reach 238 million by 2050 (Shelley *et al*., 2016). To ensure food security for this expanding population, a substantial increase in rice production will be essential.

Boosting rice production requires effective fertilizer management and the correction of micronutrient deficiencies. Micronutrient deficiencies, such as those in zinc (Zn) and Boron (B), are highly prevalent in many Asian nations, as well as Bangladesh, due to factors such as high soil pH, low organic matter,

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*Corresponding author mail: **skpaul@bau.edu.bd** salinity, drought, calcareous soils, and unbalanced fertilizer use (Akhtar *et al*., 2013; Chatzistathis, 2014; Malakouti, 2008). Zinc is essential for the synthesis of tryptophan, a precursor of the plant hormone auxin, and functions as a cofactor for over 300 enzymes. It plays a vital role in preserving the integrity of biological membranes, supporting pollen development, enhancing disease resistance, and facilitating protein synthesis and photosynthesis (Bhadra *et al*., 2023; Farooq *et al*., 2018). Rice yield increased with basal treatment of $ZnSO_4$, as reported by Zulfiqar *et al*., (2021). Research on micronutrients will help satisfy the growing demand for increased food production in the millennium, with improved nutritional content from minerals.

Boron is responsible for improved pollination, seed setting, and grain formation in various rice varieties. The maximum number of grains per panicle in the treatment plots compared to the control plots may be due to a reduction in pollen sterility of rice and proper grain filling (Bithy *et al*., 2020; Das *et al*., 2022). Fatima *et al*., (2018) stated that maximum grain yield by soil application of B at the flowering stage might be the direct effect of a higher number of grains panicle^{-1} and 1000-grain weight. Many reports indicate that B applied at the heading or flowering stage in rice resulted in increased rice grain yield and the number of grains per panicle (Hanifuzzaman *et al.,* 2022). Similarly, Rehman *et al*., (2018) reported an enhanced paddy yield due to reduced panicle sterility following B application.

Due to the deficiency and crop responses, farmers in Bangladesh have been applying zinc (Zn) and boron (B) fertilizers to their crops lately. There are numerous interactions among nutrients when they are applied to soil, and these interactions are complex and depend on a wide range of factors (Hanifuzzaman *et al*., 2022). However, to our knowledge, no study has been reported to date on the interactions and efficiency of zinc and boron fertilizers applied together in rice crops. Therefore, this study was undertaken to investigate the effect of Zn and B on the growth and yield of fine rice (cv. Binadhan-25) using both basal and foliar applications.

MATERIALS AND METHODS

Location and climate

The experiment was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh, Bangladesh (24°25′ N latitude and 90°50′ E longitude, 18 meters above sea level) from November 2023 to April 2024 to evaluate the impact of various zinc and boron application methods on the growth and yield performance of rice. The experimental site is situated on non-calcareous dark grey floodplain soil, classified under the Sonatala soil series, which falls within the Old Brahmaputra Floodplain (Agro-Ecological Zone 9, AEZ-9). The field was medium-high land with moderate drainage capacity. The soil was a silty loam in texture, with a nearly neutral pH (6.48), low organic matter content (0.88%), and contained 0.67% total nitrogen, 15.37 ppm available phosphorus, 0.23 meq/100g exchangeable potassium, and 13.46 ppm available sulfur. Soil tests indicated that available zinc (0.23 ppm) and boron (0.16 ppm) were in the deficient range. Meteorological data recorded during the experimental period (Figure 1) provided information on temperature, rainfall, and relative humidity trends, which are essential factors influencing crop growth and yield performance.

Experimental Design

The experiment was laid out using a randomized complete block design with three replications and eleven zinc and boron applications using basal and foliar methods:

1. Control (no zinc and no boron) (F_0)
2. Zn (2.0 kg ha^{-1}) and B (2.0 kg ha^{-1}) as basal (F_1)
3. 100% Zn as basal (without B) (F_2)
4. 100% B as basal (without Zn) (F_3)
5. 100% Zn foliar spray at pre-flowering stage (without B) (F_4)
6. 100% B foliar spray at pre-flowering stage (without Zn) (F_5)
7. 75% Zn and B as basal + 25% Zn and B foliar spray at pre- flowering stage (F_6)
8. 50% Zn and B as basal + 50% Zn and B foliar spray (F_7)
9. 100% Zn and B as basal + 25% Zn and B foliar spray (F_8)
10. 100% Zn and B as basal + 25% Zn foliar spray (F_9)
11. 100% Zn and B as basal + 25% B foliar spray (F_{10})

Each block was divided into 11-unit plots, where the 11 treatments were allocated at random. There was a total of 33 unit plots in the

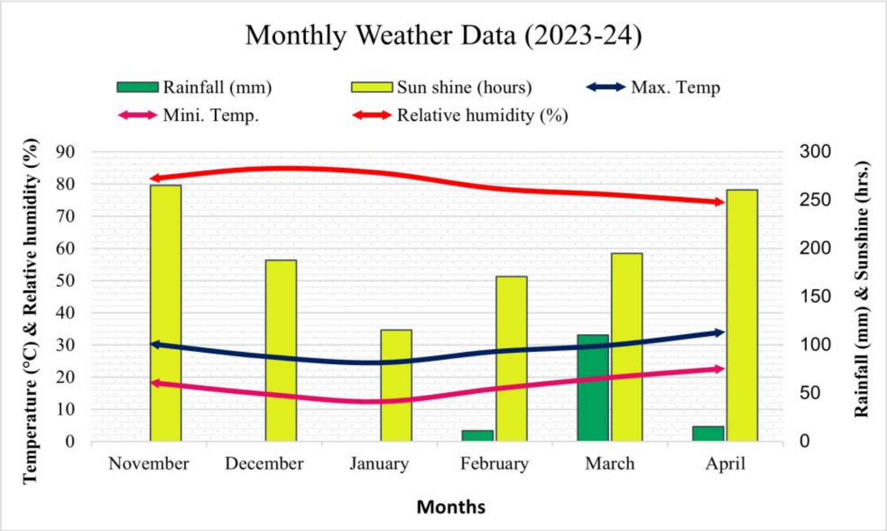


Figure 1: Meteorological data for November 2023 to February 2024 at the experimental site

experiment. The net size of each unit plot was 2.5 m × 2.0m. The spaces between replications and between plots were 1 m and 0.5 m, respectively.

Land Preparation and Intercultural Operation

Seeds of rice variety Binadhan-25 were collected from the Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh. Then the seeds were immersed in a water bucket for 24 hrs. These seeds were removed from the bucket and tightly covered with gunny bags. The seeds started sprouting after 48 hours, which became prepared for sowing within the next 72 hours.

The nursery bed was prepared by puddling, which involved repeated ploughing of nursery beds measuring 1.0 m in length and 1.0 m in width. Later, the seed was covered immediately, and then a light irrigation was given. The field was prepared by ploughing with tractor-drawn cultivators, followed by cross-harrowing to pulverize the soil. All uprooted weeds and crop residues were removed from the field after plowing and laddering. The experimental plots were fertilized with urea, triple superphosphate, and muriate of potash, as well as calcium sulfate at rates of 217, 119, 130, 77, 9.1, and 11.8 kg ha^{-1}, respectively. Except for urea, the entire amount of other fertilizers was applied before final land preparation. Urea was top-dressed in three installments at 15, 30, and 45 days after transplanting. The Zn and B were supplied at 2 kg ha^{-1} in the form of zinc sulfate and boric acid, following respective treatments. The 35-day-old seedlings were transplanted in the main field with a spacing of cm as row to row and hill to hill distance, respectively, with 2-3 seedlings per hill. A thin layer of water was maintained at the time of transplanting to facilitate the better establishment of the seedlings. From the third day onwards, a 2 to 3 cm depth of water was maintained up to the panicle initiation stage, except at the time of top dressing with urea, when the water was drained out and re-irrigated to maintain a 5 cm depth of water up to physiological maturity. After the dough stage, water was entirely drained out to make harvesting easier.

Data Collection and Harvesting

The crop was harvested at full maturity, when approximately 80% of the seeds turned golden yellow. Five hills (excluding border hills) were randomly pre-selected from each plot and uprooted before harvest to record data on various plant characteristics. After harvesting, the crops from each plot were separately bundled, tagged, and brought to the threshing floor. The crops were threshed using a pedal thresher, and the grains were sun-dried and cleaned. The straws were also properly sun-dried. Both grain and straw yields were then converted to tonnes per hectare (t ha^{-1}).

Plant height

Five hills were randomly selected soon after transplanting and marked with bamboo sticks in each plot, excluding border rows, to record the data on plant height at 45, 60, and 75 DAT. Then the plant height at 45, 60, and 75 DAT was measured from the base to the tip of the longest panicle and expressed in cm.

Total tillers hill^{-1}

Five hills were randomly selected in each plot, excluding border rows, to record the data of the number of tillers hill-1 at 45, 60, and 75 DAT. Then, the number of tillers hill^{-1} at 45, 60, and 75 DAT was measured.

Effective tillers hill^{-1}

The panicles that had at least one grain were considered effective tillers. The number of effective tillers in hill-1 was recorded and then averaged to determine the number of effective tillers in hill-1 and non-effective tillers in hill^{-1}. The tiller with no panicle was regarded as an ineffective tiller. The number of effective tillers in Hill^{-1} was recorded and then averaged to determine the number of ineffective tillers in Hill^{-1}.

Panicle length

Panicle length was recorded from the basal node of the rachis to the apex of each panicle.

Grains panicle^{-1}

Grain was considered to be filled if any kernel was present there. The number of total filled grains present on five panicles was recorded and finally averaged.

Sterile spikelet panicle^{-1}

Unfilled grains mean the absence of any kernel inside, and such grains present on each of the five panicles were counted and finally averaged.

1000-grain weight

One thousand cleaned, dried grains were randomly counted from each sample and weighed using a digital electric balance. At this stage, the grain retained about 14% moisture, and the mean weights were expressed in grams.

Grain yield

Grain yield was determined from the central 1 m^2 areas of each plot and expressed as t ha^{-1} on a basis of approximately 14% moisture. Grain moisture content was measured by using a digital moisture tester.

Straw yield

The straw yield was determined from the central 1 m^2 areas of each plot. After separating the grains, the sub-samples were oven-dried to a constant weight and finally converted to t ha^{-1}.

Biological yield

Grain yield and straw yield was all regarded together as biological yield. The biological yield was calculated with the following formula:

Biological yield (t ha^{-1}) = Grain yield (t ha^{-1}) + Straw yield (t ha^{-1})

Harvest index (%)

It denotes the ratio of grain yield to biological yield and was calculated with the following formula:

$$Harvest\ Index\ (\%) = \frac{Grain\ Yield}{Biological\ Yield} \times 100$$

Statistical Analysis

The data collected for various traits were subjected to statistical analysis to evaluate significant differences among the treatments. Analysis of Variance (ANOVA) was conducted for all recorded parameters using the R software package (R Core Team, 2024). Treatment means were compared using Duncan's New Multiple Range Test (DNMRT), as described by Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Growth Parameters

At different growth stages, growth parameters such as plant height, number of tillers per hill, and dry weight showed significant variation due to the effects of different Zn and B management treatments. The treatment F_7 (50% Zn and B as basal + 50% Zn and B as foliar spray) consistently produced the tallest plants at 45, 60, and 75 DAT, as well as at harvest, while the shortest plants were recorded in the control (F_0: no Zn and B). Treatments like F_6 (75% Zn and B as basal + 25% Zn and B foliar spray at pre-flowering stage) and F_8 (100% Zn and B as basal + 25% Zn and B foliar spray) exhibited similar trends to F_7 throughout the growth period. A similar pattern was observed for the number of tillers and dry weight. The number of tillers increased from 45 to 60 DAT, then decreased at 75 DAT, with F_7 producing the highest tiller numbers at all stages and F_0 the lowest. In terms of dry weight, F_7 recorded the highest values at 45, 60, and 75 DAT, whereas F_0 consistently showed the lowest values across all stages. The enhanced growth, dry matter accumulation, and tillering under optimal Zn and B application (basal + foliar) may be due to improved nutrient uptake and physiological functions such as enzyme activity, cell division, and sugar translocation. This balanced supply likely supported sustained growth during critical stages (Abbas *et al.*, 2013; Shaygany *et al.*, 2012; Singh *et al.*, 2021).

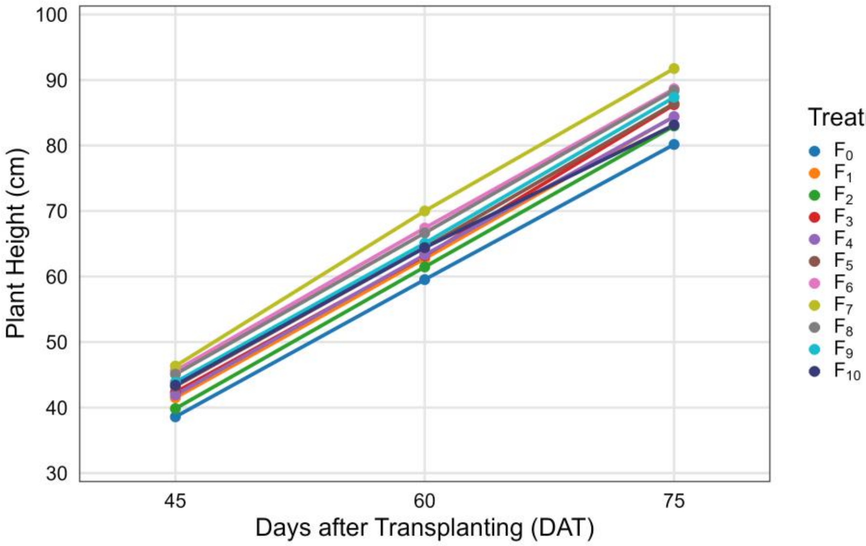


Figure 2. Effect of various zinc and boron application methods on the plant height of fine rice. Here, F_0 – Control (no Zn and B), F_1 – Zn (2.0 kg ha^{-1}) + B (2.0 kg ha^{-1}) as basal, F_2 – 100% Zn as basal (no B), F_3 – 100% B as basal (no Zn), F_4 – 100% Zn as foliar spray (no B), F_5 – 100% B as foliar spray (no Zn), F_6 – 75% Zn and B as basal + 25% as foliar spray, F_7 – 50% Zn and B as basal + 50% as foliar spray, F_8 – 100% Zn and B as basal + 25% Zn and B as foliar spray, F_9 – 100% Zn and B as basal + 25% Zn as foliar spray, F_{10} – 100% Zn and B as basal + 25% B as foliar spray.

Table 1. Effect of zinc and boron on growth attributes of fine rice (cv. Binadhan-25)

Treatments	Tillers hill^{-1} (no.)			Dry weight hill^{-1} (g)		
	45 DAT	60 DAT	75 DAT	45 DAT	60 DAT	75 DAT
F_0	5.16f	9.88f	8.83f	5.04ef	20.78e	69.56b
F_1	5.33ef	10.08f	10.00de	5.48def	21.67e	69.70b
F_2	5.41def	10.50ef	9.50ef	4.63f	22.06e	71.94b
F_3	6.16cde	10.66ef	10.25cde	5.68de	25.06d	72.90b
F_4	6.00def	10.91ef	10.40cde	4.86ef	24.98d	72.77b
F_5	6.25cd	12.23cde	10.83bcd	6.43cd	27.35cd	73.63b
F_6	7.50ab	14.25ab	13.08a	7.46ab	30.40ab	81.30a
F_7	8.00a	14.75a	14.08a	8.36a	32.57a	82.57a
F_8	7.75ab	14.00abc	11.58b	6.78bc	29.32bc	82.13a
F_9	6.91bc	12.83bcd	11.16bc	6.74bc	28.11bc	74.46b
F_{10}	6.25cd	11.91de	10.33cde	5.53def	27.54cd	73.86b
Level of Sig.	**	**	**	**	**	**
CV%	8.26	8.92	5.70	9.27	5.76	5.15

Here, in the column having similar letters do not differ significantly as per DMRT

** = Significant at 1% level of probability

F_0: (Control) (no zinc and boron), F_1: Zn (2.0 kg ha^{-1}) and B (2.0 kg ha^{-1}) as basal, F_2: 100% Zn as basal (without B), F_3: 100% B as basal (without Zn), F_4: 100% Zn foliar spray at pre-flowering stage (without B), F_5: 100% B foliar spray at pre- flowering stage (without Zn), F_6: 75% Zn and B as basal + 25% Zn and B foliar spray at pre- flowering stage, F_7: 50% Zn and B as basal + 50% Zn and B foliar spray, F_8: 100% Zn and B as basal + 25% Zn and B foliar spray, F_9: 100% Zn and B as basal + 25% Zn foliar spray, F_{10}: 100% Zn and B as basal + 25% B foliar spray

Our results are supported by some previous studies (Chattha *et al*., 2023; Hanifuzzaman *et al*., 2022; Nishad *et al.,* 2025) where it is observed that different doses and methods of Zn subsequently influence growth of rice and B. Arif *et al*., (2012) reported that improvement in rice growth parameters related to Zn and B is associated with the development of cell wall and cell differentiation and hence, helps in root elongation and shoot growth of plant.

Yield components and yield

The application of different levels and combinations of zinc (Zn) and boron (B) fertilizers significantly influenced the growth parameters, yield attributes, and yield of rice. Agronomic traits such as total tillers hill^{-1}, effective tillers hill^{-1}, non-effective tillers hill^{-1}, panicle length, grains panicle^{-1}, sterile spikelets panicle^{-1}, 1000-grain weight, grain yield, straw yield, biological yield, and harvest index were all markedly affected by the fertilizer treatments. The highest number of total tillers hill^{-1} was observed in treatment F_7 (50% Zn and B as basal + 50% as foliar spray), which was statistically similar to F_6 (75% Zn and B as basal + 25% foliar spray at pre-flowering) and F_8 (100% Zn and B as basal + 25% foliar). The lowest number was recorded in the control (F_0). A similar trend was observed for effective tillers hill^{-1}, where F_7 produced the highest count, followed by F_6, while the lowest was in F_0. Treatment F_7 enhanced the number of effective tillers by 37.36% compared to the control. In contrast, the highest number of non-effective tillers hill^{-1} was also recorded in F_7, whereas the lowest was found in F_4 (100% Zn foliar spray). The maximum panicle length was observed in F_7, while the minimum occurred in F_3 (100% B as basal). Among the yield components, the number of grains panicle^{-1} and 1000-grain weight were highest in F_7, followed by F_8, with the control showing the lowest values. Notably, F_7 resulted in approximately a 15% increase in 1000-grain weight compared to F_0. The highest number of sterile spikelets panicle^{-1} was found in F_3, whereas the lowest (11.00) was recorded in F_6.

The treatments significantly influenced grain yield. The highest grain yield (6.98 t ha^{-1}) was obtained in F_7, which was statistically comparable to F_6, while the lowest (5.82 t ha^{-1}) was observed in the control. The combined application of Zn and B (50% basal + 50% foliar) resulted in a yield increase of approximately 20% over the control, 2% over 100% Zn basal application, and 9% over 100% B basal application. Separate foliar applications of Zn or B increased yield by 7.3% and 12.18%, respectively. Similarly, the highest straw yield (7.42 t ha^{-1}), biological yield (14.40 t ha^{-1}), and harvest

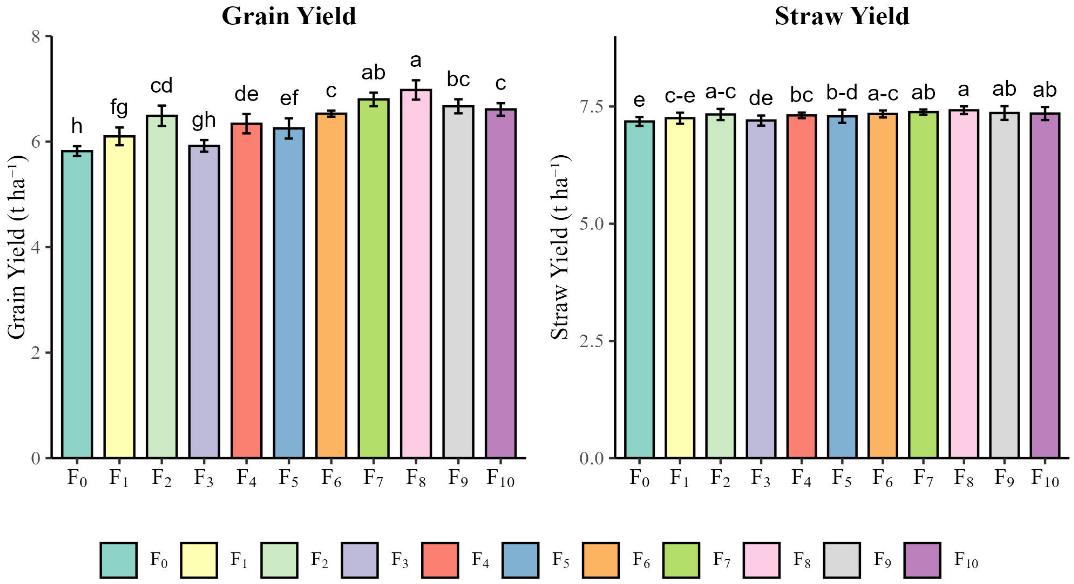


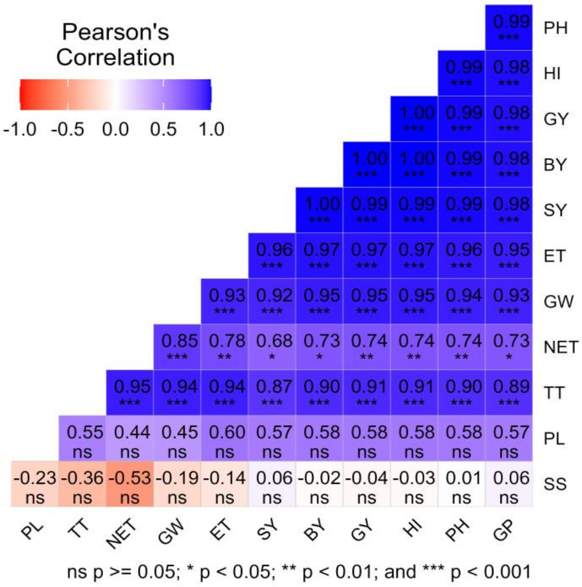
Figure 3: Effect of various zinc and boron application methods on the grain yield and straw yield of fine rice. Here, F_0 – Control (no Zn and B), F_1 – Zn (2.0 kg ha^{-1}) + B (2.0 kg ha^{-1}) as basal, F_2 – 100% Zn as basal (no B), F_3 – 100% B as basal (no Zn), F_4 – 100% Zn as foliar spray (no B), F_5 – 100% B as foliar spray (no Zn), F_6 – 75% Zn and B as basal + 25% as foliar spray, F_7 – 50% Zn and B as basal + 50% as foliar spray, F_8 – 100% Zn and B as basal + 25% Zn and B as foliar spray, F_9 – 100% Zn and B as basal + 25% Zn as foliar spray, F_{10} – 100% Zn and B as basal + 25% B as foliar spray.

index (48.46%) were recorded in F7. In contrast, the control recorded the lowest values for these parameters (7.18 t ha⁻¹, 13.00 t ha⁻¹, and 44.77%, respectively). The improvement in yield attributes can be attributed to enhanced nutrient uptake and utilization efficiency, which supports key physiological processes such as photosynthesis, better assimilate partitioning, and optimized reproductive development. The synergistic effect of Zn and B likely addressed specific micronutrient deficiencies, promoting overall plant vigor and, ultimately, higher yield.

These findings are consistent with previous studies involving basal and foliar applications of Zn and B in rice and other agronomic crops (Nishad *et al.,* 2025; Quddus *et al.,* 2011; Yogi *et al*., 2024). Arif *et al*., (2012) found that the synergy of zinc and boron in combined use demonstrated a notably greater increase in crop yield compared to their application. Soltani *et al*., (2020) reported that the maximum spikelets per panicle, grains per panicle, 1000-grain weight, grain yield, and biomass were achieved with basal Zn application. In contrast, foliar application at maximum tillering and flowering stages yielded the highest values for these traits. Nishad *et al.,* (2025) stated that foliar and soil application of Zinc fertilizer enhanced early seedling growth in rice genotypes by improving agronomic traits associated with water use and biochemical properties. Higher harvest index values reflect more efficient translocation of photosynthates from the source to the sink, indicating improved allocation of resources towards reproductive growth (Saikh *et al*., 2022).

Correlation Analysis

Pearson's correlation coefficients were computed to examine the relationships among growth, yield, and yield-contributing traits of rice under different Zn and B fertilizer treatments (Figure 4). Grain yield (GY) exhibited a strong positive correlation ($p < 0.001$) with all major yield components and agronomic traits, including biological yield (BY), straw yield (SY), effective tillers hill⁻¹ (ET), 1000-grain weight (GW), total tillers hill⁻¹ (TT), panicle length (PL), and grains panicle⁻¹ (GP). Similarly, biological yield had perfect or near-perfect positive correlations with SY, ET, GW, TT, and GY. The harvest index showed significant positive associations with GY, ET, GW, TT, and GP, further highlighting the yield dependency on these traits. Effective tillers hill⁻¹ (ET) were significantly and positively correlated with TT, GW, and SY. Total tillers hill⁻¹ (TT) showed strong correlations with GW, SY, and PH. Plant height (PH) was positively associated with almost all traits, notably TT, HI, and GY.



	PL	TT	NET	GW	ET	SY	BY	GY	HI	PH	GP
PH											0.99 ***
HI										0.99 ***	0.98 ***
GY									1.00 ***	0.99 ***	0.98 ***
BY								1.00 ***	1.00 ***	0.99 ***	0.98 ***
SY							1.00 ***	0.99 ***	0.99 ***	0.99 ***	0.98 ***
ET						0.96 ***	0.97 ***	0.97 ***	0.97 ***	0.96 ***	0.95 ***
GW					0.93 ***	0.92 ***	0.95 ***	0.95 ***	0.95 ***	0.94 ***	0.93 ***
NET				0.85 ***	0.78 **	0.68 *	0.73 *	0.74 **	0.74 **	0.74 **	0.73 *
TT			0.95 ***	0.94 ***	0.94 ***	0.87 ***	0.90 ***	0.91 ***	0.91 ***	0.90 ***	0.89 ***
PL		0.55 ns	0.44 ns	0.45 ns	0.60 ns	0.57 ns	0.58 ns	0.58 ns	0.58 ns	0.58 ns	0.57 ns
SS	-0.23 ns	-0.36 ns	-0.53 ns	-0.19 ns	-0.14 ns	0.06 ns	-0.02 ns	-0.04 ns	-0.03 ns	0.01 ns	0.06 ns

ns p >= 0.05; * p < 0.05; ** p < 0.01; and *** p < 0.001

Figure 4: Pearson correlation matrix illustrating the relationships among growth and yield-related traits of fine rice under different zinc (Zn) and boron (B) management treatments. Trait abbreviations: PH – Plant height (cm), TT – Total tillers hill⁻¹, ET – Effective tillers hill⁻¹, NET – Non-effective tillers hill⁻¹, PL – Panicle length (cm), GP – Grains panicle⁻¹ (no.), SS – Sterile spikelets (no.), GW – 1000-grain weight (g), GY – Grain yield (t ha⁻¹), SY – Straw yield (t ha⁻¹), BY – Biological yield (t ha⁻¹), HI – Harvest index (%).

In contrast, sterile spikelets panicle⁻¹ displayed weak to negative correlations with most traits, though not statistically significant ($p \geq 0.05$). It was negatively correlated with ET, GW, TT, and PL, suggesting a detrimental role of spikelet sterility in yield performance. Overall, the correlation matrix confirmed that effective tillering, panicle traits, and grain weight are strongly associated with higher yield performance, while increased spikelet sterility has an adverse effect.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed to explore the interrelationships among the measured agronomic traits and to assess the variation in rice responses under different Zn and B fertilizer treatments (Figure 5). The first two principal components (Dim1 and Dim2) accounted

Table 2. Effect of zinc and boron on yield-regulating characters of fine rice (cv. Binadhan-25)

Treatments	Plant height (cm)	Non-effective tillers hill^{-1} (no.)	Effective tillers hill^{-1} (no.)	1000-grain weight (g)	Panicle length (cm)	Grains panicle^{-1} (no.)	Sterile spikelets (no.)	Biological yield (t ha^{-1})	Harvest index (%)
F_0	110.10e	0.35c	7.20h	19.06d	27.27ef	138.13b	11.43de	13.00h	44.77h
F_1	111.56cde	0.06de	8.05f	19.13d	27.48cd	140.15ab	11.69cde	13.35fg	45.69fg
F_2	110.89de	0.40c	7.55g	19.10d	27.40de	139.78ab	11.51de	13.12gh	45.12gh
F_3	112.53abcd	0.30cd	8.26de	19.99c	27.13f	142.52ab	13.35a	13.65de	46.44de
F_4	112.05bcde	0.02e	8.13ef	19.18d	27.68ab	141.44ab	13.00ab	13.54ef	46.15ef
F_5	113.13abcd	0.30cd	8.60c	20.35c	27.74a	143.56ab	12.22bcd	13.87cd	47.07c
F_6	114.35a	1.87ab	9.06b	21.63a	27.61abc	144.79ab	11.00e	14.18ab	47.95ab
F_7	114.66a	2.11a	9.89a	21.88a	27.71a	145.88a	11.05e	14.40a	48.46a
F_8	114.12ab	1.67b	8.96b	21.08b	27.69ab	145.52a	12.43bc	14.03bc	47.54bc
F_9	113.46abc	0.47c	8.73c	20.98b	27.42de	143.92ab	12.99ab	13.96bc	47.34bc
F_{10}	113.08abcd	0.33c	8.30d	20.15c	27.54bcd	142.98ab	12.87ab	13.82cd	46.96cd
Level of Significance	**	**	**	**	**	*	**	**	**
CV%	3.18	10.63	3.95	3.59	2.33	2.88	4.10	5.01	3.78

Here, in the column having similar letters do not differ significantly as per DMRT

** = Significant at 1% level of probability

F_0: (Control) (no zinc and boron), F_1: Zn (2.0 kg ha^{-1}) and B (2.0 kg ha^{-1}) as basal, F_2: 100% Zn as basal (without B), F_3: 100% B as basal (without Zn), F_4: 100% Zn foliar spray at pre-flowering stage (without B), F_5: 100% B foliar spray at pre- flowering stage (without Zn), F_6: 75% Zn and B as basal + 25% Zn and B foliar spray at pre- flowering stage, F_7: 50% Zn and B as basal + 50% Zn and B foliar spray, F_8: 100% Zn and B as basal + 25% Zn and B foliar spray, F_9: 100% Zn and B as basal + 25% Zn foliar spray, F_{10}: 100% Zn and B as basal + 25% B foliar spray for a cumulative 92.3% of the total variability, with Dim1 explaining 80.6% and Dim2 explaining 11.7%. Treatments F$_7$ and F$_6$ were positively associated with key yield-contributing parameters, such as total tillers hill^{-1} (TT), effective tillers hill^{-1} (ET), panicle length (PL), 1000-grain weight (GW), and grains panicle^{-1} (GP), grain yield (GY), straw yield (SY), biological yield (BY), and harvest index (HI). This indicates that moderate to balanced combined applications of Zn and B (both basal and foliar) contributed substantially to improved performance in these traits. In contrast, treatments F$_0$ (control) and F$_2$ were distantly positioned from most of the yield-related traits, suggesting poor performance across those parameters. Treatments F$_3$ and F$_4$ were positively aligned with sterile spikelets panicle^{-1} (SS), indicating higher spikelet sterility and hence lower yield performance. Overall, the PCA analysis revealed that treatment F7, and to a lesser extent F6 and F8, effectively enhanced yield and yield components in rice through integrated Zn and B nutrient management.

Functional relationship between the number of tillers hill^{-1} and grain yield

A positive linear relationship between grain yield and number of tillers hill^{-1} at 60 DAT of fine rice, which indicated that the higher the number of tillers hill^{-1}, the higher the grain yield (t ha^{-1}). The relationship between the number of tillers per hill^{-1} and the grain yield of fine rice was determined using the respective interaction data between Zn and B fertilizer application. The response of the number of hills on the grain yield of fine rice followed a linear positive relationship, which could be adequately described by the regression equation $Y = 4.5452x - 17.135$ ($R^2 = 0.8858$), as shown in Figure 6. A similar result was also observed by Paul *et al.,* (2021).

Functional relationship between dry weight and grain yield

The response of total dry matter at 60 DAT to the grain yield of fine rice followed a linear positive relationship, which could be adequately described

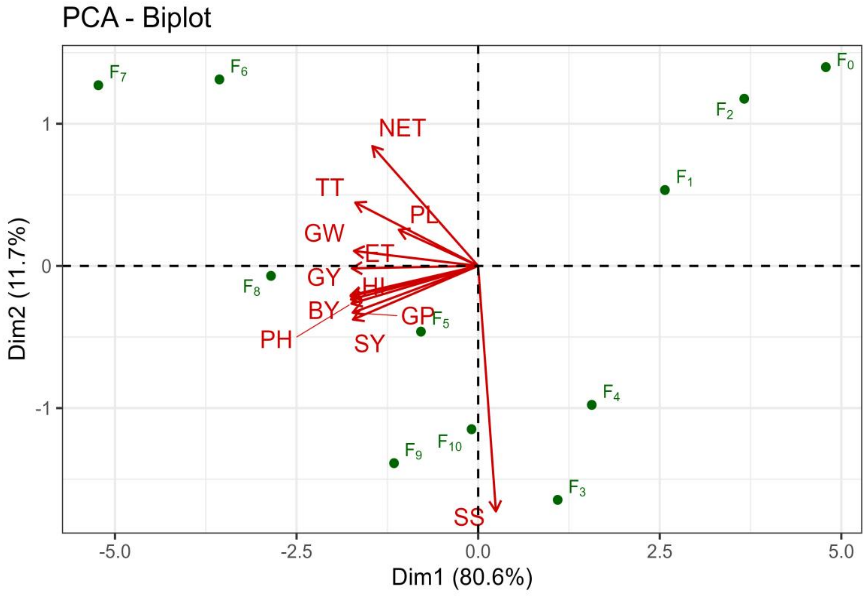


Figure 5: Biplot of principal component analysis (PCA) showing the distribution of growth and yield-related traits of fine rice across different zinc (Zn) and boron (B) management treatments. The first two principal components (Dim 1 and Dim 2) represent the significant variation among traits and treatments. Trait abbreviations: PH – Plant height (cm), TT – Total tillers hill^{-1}, ET – Effective tillers hill^{-1}, NET – Non-effective tillers hill^{-1}, PL – Panicle length (cm), GP – Grains panicle^{-1}, SS – Sterile spikelets (no.), GW – 1000-grain weight (g), GY – Grain yield (t ha^{-1}), SY – Straw yield (t ha^{-1}), BY – Biological yield (t ha^{-1}), HI – Harvest index (%). Treatments: F0 – Control (no Zn and B), F1 – Zn (2.0 kg ha^{-1}) + B (2.0 kg ha^{-1}) as basal, F2 – 100% Zn as basal (no B), F3 – 100% B as basal (no Zn), F4 – 100% Zn as foliar spray (no B), F5 – 100% B as foliar spray (no Zn), F6 – 75% Zn and B as basal + 25% as foliar spray, F7 – 50% Zn and B as basal + 50% as foliar spray, F8 – 100% Zn and B as basal + 25% Zn and B as foliar spray, F9 – 100% Zn and B as basal + 25% Zn as foliar spray, F10 – 100% Zn and B as basal + 25% B as foliar spray.

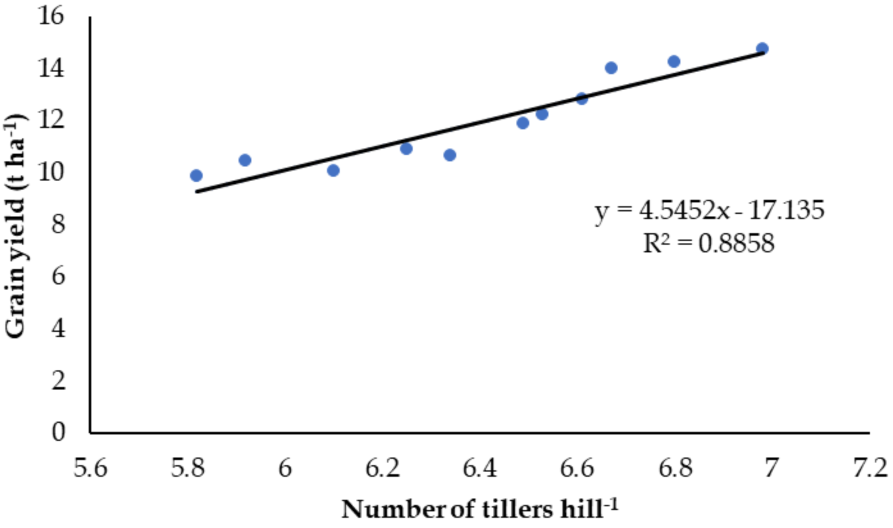


Figure 6: Functional relationship between the number of tillers hill^{-1} and the grain yield of fine rice

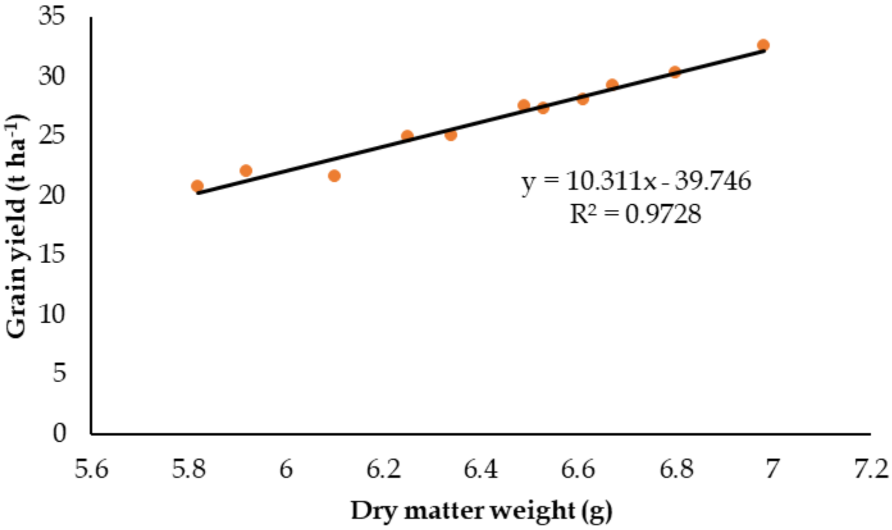


Figure 7: Functional relationship between dry matter weight and grain yield of fine rice

by a regression equation. In Figure 7, the regression equation suggests that an increase in dry weight is associated with a corresponding increase in fine rice grain yield. The functional relationship can be determined by the regression equation Y = 10.311x - 39.746 (R^2 = 0.9728) (Figure 7). A similar result was also observed by Paul *et al.*, (2021).

CONCLUSION

This study emphasizes the importance of addressing micronutrient deficiencies, specifically zinc and boron, to improve rice productivity in Bangladesh. The combined application of 50% Zn and B as basal and 50% as foliar spray significantly improved key growth parameters and yield components of Binadhan-25, including plant height, tiller number, grain yield (6.98 t ha^{-1}), and harvest index (48.46%), compared to the control. These findings highlight the importance of balanced micronutrient management in conjunction with NPK fertilization for sustainable rice production. The study offers a practical approach for enhancing nutrient use efficiency and improving crop performance. However, its single-location and single-season design limits the generalizability of the results. Future research should evaluate the effectiveness of this approach across diverse rice varieties, soil conditions, and agro-ecological zones, along with a cost-benefit analysis to support its adoption by farmers.

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Author Contributions:

MM: Writing – original draft, Visualization, Methodology, Data curation, Formal analysis. AM: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Formal analysis. MRU: Methodology, Conceptualization, Supervision, Writing – review & editing. UKS: Methodology, Investigation, Validation, Writing – original draft, Writing – review & editing. MRH: Data curation, Methodology, Formal analysis, Writing – review & editing. SKP: Conceptualization, Supervision, Data curation, Formal analysis, Writing – review & editing, Writing– original draft, Visualization, Validation.

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