International Journal of Scientific Research in Multidisciplinary Studies
Vol.10, Issue.8, pp.52-58, August 2024
E-ISSN: 2454-9312 P-ISSN: 2454-6143
Available online at: www.isroset.org

Research Article

Comparative Study of Zinc Doses and Application Methods Ensuring Maximum Productivity of Boro Rice

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Received: 16/Jun/2024; **Accepted**: 18/Jul/2024; **Published**: 31/Aug/2024

Abstract— The experiment was conducted at the Agronomy Field Laboratory, Department of Agronomy and Agricultural Extension, University of Rajshahi from January to May 2020 to study the effects of different zinc application methods on the growth and yield of three boro rice varieties: BRRI dhan28, BRRI dhan29, and BRRI dhan58. The study employed a factorial Randomized Complete Block Design with three Zn treatments: root dipping in Zn solution just before transplanting (T_1), foliar application of Zn at the tillering stage (T_2), and foliar application of Zn at both the tillering and flowering stages (T_3). The results demonstrated that Zn application significantly affected plant height, total tillers, panicle length, and yield parameters. Among the varieties, BRRI dhan58 (V_3) consistently exhibited superior growth and yield. The T_3 treatment, involving foliar application at both the tillering and flowering stages, produced the highest plant height, total tillers, effective tillers, panicle length, and grain yield compared to T_1 and T_2. Specifically, the V_3T_3 combination achieved the highest grain yield (6.82 t ha^{-1}) and straw yield (9.13 t ha^{-1}). This study highlights the critical role of Zn management in optimizing boro rice production, with the dual-stage foliar application proving to be the most effective in enhancing crop growth and yield.

Keywords— *Zinc Fertilization, Application methods, Growth stages, Maximum productivity*.

1. Introduction

More than half of the global population relies on rice (*Oryza sativa* L), the most significant food crop raised worldwide, as their primary source of nutrition [1]. Bangladesh places great emphasis on the economic and social importance of rice (*Oryza sativa* L.), which is part of the Gramineae family. The nation's agricultural environment is dominated by rice, the most widely grown crop and primary food. In order to maintain food security and support the national economy, the boro rice season is especially important. The BBS reported that 36.60 million tons of rice were produced on around 11.42 million hectares of rice-cultivated land, while the boro season produced 19.646 million metric tons of rice from 47.63 million hectares of land [2]. Improving the yield per unit area becomes essential due to the restricted amount of arable land available [3]. Better agriculture technology and careful fertilizer management techniques are therefore required. Achieving optimal crop production is largely dependent on the nutritional state of the soil [4], particularly on the availability of micronutrients like zinc [5]. Zinc, though required in trace amounts, is vital for the proper growth of rice plants. It influences fruit size, is an integral part of the carbonic enzyme in photosynthetic tissues, and is essential for chlorophyll biosynthesis [6], [7]. The deficiency of Zinc is a widespread issue, particularly in high pH calcareous soils, and poses a significant barrier to achieving higher crop yields [8]. The solubility of Zinc in soil rather than its total amount is the primary reason for this deficiency, impacting physiological functions such as protein synthesis, enzyme activation, and carbohydrate metabolism [9], [10]. Consequently, the failure to supply Zinc in inadequate amounts can lead to physiological stress in plants, preventing high-yielding varieties like BRRI dhan28, BRRI dhan29, and BRRI dhan58 from realizing their full potential [11]. In this context, the present study aims to explore the efficacy of different doses and application methods of Zinc on the growth and yield of boro rice. The specific objectives are to investigate the effect of Zinc on the growth and yield of boro rice (BRRI dhan28, BRRI dhan29, BRRI dhan58) and to determine the optimum level of Zinc required for achieving the potential yield of boro rice.

2. Materials and Methods

The experiment was conducted at the Agronomy Field Laboratory, Department of Agronomy and Agricultural Extension, University of Rajshahi, during the period from January 2020 to May 2020 to investigate the influence of varieties and different doses of zinc on growth and yield of boro rice. A comprehensive account of the materials and methodologies used throughout the experimental period is provided. It includes a detailed description of the characteristics of the experimental soil and climatic conditions, along with the design of the experiment and the specific treatments applied. It also covers the various cultural practices implemented during the experiment, such as planting techniques, irrigation, and pest management. Additionally, the process of data collection is thoroughly explained, including the parameters measured and the timing of observations. Finally, the statistical methods used to analyse the collected data are discussed, ensuring a clear understanding of how the results were derived. Each of these components is addressed in detail in the sections that follow.

2.1 Soil and climate: The experimental site was characterized by sandy loam soil, with a pH level measured at 7.6, indicating slightly alkaline conditions. The field was situated in a region with a subtropical climate, where the kharif season, spanning from November to March, was typified by moderately high temperatures and abundant rainfall. This seasonal pattern provided favourable growing conditions during the early stages of the experiment. Conversely, the Rabi season, also from November to March, experienced a significant reduction in rainfall, coupled with moderately cooler temperatures. These contrasting climatic conditions influenced the growth and development of the crops throughout the experiment.

2.2 Variety and Experimental treatments: The three rice varieties (BRRI dhan28, BRRI dhan 29 and BRRI dhan 58) were used in the present experiment. All variety ware collected from Bangladesh Rice Research Institute (BRRI), Regional Station, Shampur, Rajsahi. Two factors were included in the experiment namely variety (V_1= BRRI dhan28, V_2= BRRI dhan29, V_3= BRRI dhan58) and fertilizer (T_1= Deeped in Zinc solution just before transplanting, T_2= Foliar application of zinc at tillering stage, T_3= foliar application of zinc both at tillering stage and flowering stage)

2.3 Cultivation techniques: Healthy seeds were soaked for 24 hours, sprouted in darkness, and sown in a prepared seedbed in January 2020. The seedbed was maintained with weeding, irrigation, and pest protection. For transplanting, the field was initially flooded to rot weeds, then ploughed and leveled. The final preparation for transplanting occurred on 26 February 2020, with layout completed on 15 February. NPK fertilizers (urea, TSP, MP) were applied as recommended by BARI during the growth stage. Seedlings were uprooted and transplanted on 26 February using conventional methods. Intercultural operations included gap filling, manual weeding, herbicide application, flood irrigation, and pest control. Infestations by rice stem borers and green leafhoppers were managed with Furadan and Sumithion. Regular observations ensured the plants grew healthily, showing vigorous tiller growth without lodging. Data were collected from three randomly selected hills per plot at 30-day intervals until harvest. The crop was harvested on 1 June at full maturity. Post-harvest, each plot's crop was bundled, tagged, and threshed separately. The grains and straw were sun-dried, adjusted to 14% moisture, and yields were converted to tons per hectare. The field appeared healthy throughout the growing period, with no major disease incidences. The crop was harvested at full maturity.

2.4 Collection of experimental data: The data collection process involved several key measurements to assess the growth and yield of the rice plants throughout the experiment. Plant height was meticulously recorded at various growth stages 21, 42, 63, and 84 days after transplanting (DAT) as well as at maturity. These measurements were taken from three randomly selected plants within each plot to ensure accuracy and representativeness. The total number of tillers per hill, encompassing both productive and unproductive tillers, was also counted from the same selected plants. Chlorophyll content, an indicator of plant health, was measured using a SPAD-502 meter to gauge the photosynthetic efficiency of the plants. At the point of maturity, yield-related data were gathered by carefully uprooting three hills from each plot, while border rows were excluded to avoid edge effects. The crop was harvested from a designated 1m² area within the plot. The recorded data encompassed a comprehensive set of growth and yield parameters, including plant height (cm), total tillers per hill, effective and non-effective tillers per hill, panicle length (cm), weight of 1,000 grains (g), grain yield (t ha^{-1}), straw yield (t ha^{-1}), biological yield (t ha^{-1}), and harvest index (%). Grain and straw yields were then dried and converted to tons per hectare to facilitate comparisons. The biological yield was calculated by summing the grain and straw yields, providing an overall measure of the total biomass produced. Finally, the harvest index, representing the efficiency of the plant in converting biomass into economic yield, was determined as the ratio of grain yield to biological yield.

2.5 Statistical analysis: The collected data underwent analysis utilizing the "STATVIEW" statistical package. Mean differences were evaluated employing Duncan's multiple-range test ($P \leq 0.05$) with the help of SPSS software.

3. Results

3.1 Plant height: Rice varieties differed considerably at early development stages (21 and 42 days after transplanting, DAT) and became non-significant at advanced growth stages (63 and 84 DAT) (Table-1). At 21 DAT, V_3 (BARI dhan58) had the maximum plant height (37.64cm), which decreased marginally by 2.15 percent in V_2 (BRRI dhan29), but considerably by 6.96 percent in V1 (BRRI dhan28). At 42 DAT, V_3 had the maximum plant height (63.32cm), which declined just 1.16 percent in V_2 but considerably by 2.11 percent in V_1. At 63 DAT, V3 had the highest plant height (78.23cm), while V_1 had the lowest (74.97cm). At 84 DAT, V_3 had the highest plant height (86.19cm), while V_1 had the lowest (82.55cm). The plant height of rice differed significantly due to application of different Zn fertilization at all observations (21, 42, 63 and 84 DAT). At 21 DAT, the highest plant height (38.39 cm) was observed in T_3 (foliar application of Zinc at tillering and flowering stage), which reduced significantly by 5.97 % and 10.05 % in T_2 (foliar application of Zinc at tillering stage) and T_1 (root dipped in

Zinc solution just before transplanting), respectively. At 42 DAT, the highest plant height (63.72 cm) was observed in V_3, which reduced significantly by 1.91 % and 3.25 % in T_2 and T_1 respectively. At 63 DAT, the highest plant height (79.59 cm) was observed in V_3, which reduced significantly by 4.11 % and 7.56 % in T_2 and T_1 respectively. At 84 DAT, the highest plant height (87.90 cm) was observed in V_3, which reduced significantly by 4.64 % and 7.70 % in T_2 and T_1 respectively. Rice plant height variation was statistically significant owing to interaction between cultivars and zinc fertilization at all observations (21, 42, 63, and 84 DAT). At 21 DAT, the maximum plant height (39.05 cm) was found in V_3T_3 and the lowest (33.85 cm) in V_1T_1. At 42 DAT, the maximum plant height (64.01 cm) was found in V_3T_3 and the lowest (61.13 cm) in V_1T_1. At 63 DAT, the maximum plant height (80.25 cm) was reported in V_3 with T_3 and the lowest (72.38 cm) in V_1 with T_1. At 84 DAT, the maximum plant height (88.63 cm) was found in V_3T_3 and the lowest (80.10 cm) in V_1T_1 (Table 1).

3.2 Total number of tiller hill^{-1}: Due to varietal variations, the total number of tiller hill^{-1} of rice changed considerably at 21, 42, 63, and 84 DAT (Table 1). The largest number of tillers (13.15) was reported in V_3, which decreased marginally by 6.35 percent in V_2 but dramatically by 9.73 percent in V_1.

Due to Zn fertilization, the total number of rice tiller hill^{-1} changed considerably at 21, 42, 63, and 84 DAT. T_3 had the most tillers (18.04), which decreased dramatically by 8.81 percent and 15.76 percent in T_2 and T_1, respectively. Significant differences were observed due to interaction effect of rice varieties and Zn fertilizations. The highest no of tiller hill^{-1} (18.33) was observed in V_3T_3 and the lowest no of tiller hill^{-1} (14.56) was in V_1T_1 (Table 1).

3.3 Number of effective tillers hill^{-1}: There were no significant differences in the number of effective tiller hill^{-1} in rice varieties (Table 1). V_3 had the highest number of effective tillers (13.15), while V_1 had the lowest number of effective tillers. The number of effective tillers per hill^{-1} varied significantly as a result of Zn fertilization. T_3 had the highest number of effective tillers (13.96) and T_1 had the lowest number of effective tillers (9.89). Significant differences were observed due to the interaction effects of rice varieties and Zn fertilization. The highest no of effective tiller hill^{-1} (14.33) was observed in V_3T_3 and the lowest no of effective tiller hill^{-1} (9.22) was observed in both V_1T_1 and V_2T_1 (Table 1).

3.4 Number of non-effective tiller hill^{-1}: The number of non-effective tiller of rice did not differ significantly in rice varieties (Table 1). The highest number of non-effective tiller hill^{-1} (4.93) was observed in V_1 and the lowest (4.33) was found in V_3. Significant differences were observed in number of non-effective tiller hill^{-1} of rice due to the Zn fertilization. The highest number of non-effective tiller hill^{-1} of rice (5.26) was found in T_1, which reduced significantly by 22.60 % and 10.65% in T_3 and T_2 respectively. Significant differences were observed due to the interaction effects of rice varieties and Zn fertilization. The highest no of non-effective tiller hill^{-1} (14.33) was observed in V_3T_3 and the lowest no of non-effective tiller hill^{-1} (9.22) was observed in both V_1T_1 and V_2T_1 (Table 1).

3.5 Panicle Length: The panicle length of rice differed significantly in case of rice varieties (Table 2).The highest

Table 1: Effect of zinc fertilization on growth parameters of boro rice

Variety	Plant Height (cm)				Total no of tiller hill^{-1}	No of effective tiller hill^{-1}	No of non-effective tiller hill^{-1}
	21 DAT	42 DAT	63 DAT	84 DAT			
V_1	35.19±0.67b	61.98±0.40b	74.97±1.60	82.55±1.24	15.78±0.53b	10.85±0.79	4.93±0.28
V_2	36.19±0.86ab	62.58±0.43ab	76.28±1.18	84.11±1.35	16.37±0.58ab	11.59±0.84	4.78±0.27
V_3	37.64±0.77a	63.32±0.32a	78.23±1.21	86.19±1.18	17.48±0.45a	13.15±0.71	4.33±0.27
Treatment							
T_1	34.53±.47b	61.65±0.31b	73.57±0.56c	81.13±0.73b	15.14±0.37b	9.89±0.50c	5.26±0.15a
T_2	36.10±0.75b	62.50±0.37b	76.32±1.16b	83.82±1.13b	16.45±0.52b	11.74±0.77b	4.70±0.26ab
T_3	38.39±0.67a	63.72±0.23a	79.59±0.96a	87.90±0.93a	18.04±0.30a	13.96±0.55a	4.07±0.27b
Interaction							
V_1T_1	33.85±0.48c	61.13±0.37c	72.38±0.49d	80.10±1.07d	14.56±0.40d	9.22±0.59c	5.33±0.19ab
V_1T_2	34.25±0.65bc	61.48±0.37c	73.55±0.86d	80.71±0.65d	15.11±0.48d	9.78±0.62c	5.33±0.19ab
V_1T_3	37.47±0.92ab	63.33±0.46ab	78.98±1.67ab	86.84±1.73abc	17.67±0.51abc	13.56±1.06ab	4.11±0.59bc
V_2T_1	33.94±0.49c	61.34±0.31c	73.30±0.66d	80.31±1.01d	14.67±0.39d	9.22±0.59c	5.44±0.22a
V_2T_2	35.99±1.00abc	62.57±0.60abc	75.99±1.82abc	83.77±1.35bcd	16.33±0.77bcd	11.56±1.16abc	4.78±0.40abc
V_2T_3	38.64±1.42a	63.82±0.47ab	79.54±1.76ab	88.24±1.78ab	18.11±0.59ab	14.00±1.07ab	4.11±0.48bc
V_3T_1	35.82±0.96abc	62.50±0.60bc	75.03±1.16bc	82.97±1.29cd	16.22±0.68cd	11.22±0.97bc	5.00±0.33abc
V_3T_2	38.06±1.29a	63.45±0.41ab	79.42±1.88ab	86.97±1.82abc	17.89±0.68abc	13.89±1.06ab	4.00±0.39c
V_3T_3	39.05±1.35a	64.01±.31a	80.25±2.19a	88.63±1.82a	18.33±0.58a	14.33±1.07a	4.00±0.51c
CV(%)	4.81	1.23	3.4	2.97	6.03	13.68	14.51

The mean followed by different letter(s) in a column differed significantly, CV= Co-efficient of variation, LS= Level of significant, DAT= Days After Transplanting, $V_{1=}$BRRI dhan28, $V_{2=}$ BRRI dhan29, $V_{3=}$BRRI dhan58, T_1= Deeped in Zinc solution just before transplanting, T_2= Foliar application of zinc at tillering stage , T_3= Foliar application of zinc at both tillering and flowering stage panicle length (20.61cm) was observed in V_3, which reduced slightly by 2.09 % in V_2 but significantly by 4.08 % in V_1. Significant differences were observed in panicle length of rice due to the Zn fertilization. The larger panicle (20.93cm) was observed in T_3, which reduced significantly by 3.82 % and 6.78 % in T_2 and T_1 respectively. The variation in panicle length of rice was statistically significant due to interaction between varieties and zinc fertilizations. The highest panicle length (21.03cm) was observed in V_3T_3 and the lowest (19.22cm) in V_1T_1 (Table 2).

3.6 Number of grains per panicle: The number of grains per panicle of rice was not differed significantly (Table 2). The highest number of grains per panicle (169.00) was observed in V_3 and the lowest (156.00) was observed in V_1. The number of grains per panicle of rice differed significantly due to application of Zn fertilizer. The highest number of grains per panicle (175.78) was observed in T_3, which reduced significantly by 8.14 % and 14.83 % in T_2 and T_1 respectively. The number of grains per panicle of rice differed significantly due to interaction of varieties and application of Zn fertilizer. More grains per panicle (176.89) were observed in V_3T_3 and fewer grains per panicle (145.89) were found in V_1T_1 (Table 2).

3.7 Thousand (1000) grain weight (g): The 1000 grain weight of rice was not differed significantly in case of rice varieties (Table 2). The highest 1000 grain weight (23.20g) was observed in V_1 and the lowest (22.34g) in V_3. The 1000 grain weight of rice differed significantly. The highest 1000 grain weight (23.20g) was observed in T_2, which was reduced significantly by 3.97 % and 1.12% in T_3 and T_1 respectively. Significant differences were observed in the 1000 grain weight of rice due to interaction of varieties and the application of Zn fertilizer. The highest 1000 grain weight (23.53g) was observed in V_1T_2 and the lowest was found (21.76g) in V_3T_3 combination (Table 2).

3.8 Grain Yield (t ha^{-1}): Significant differences in grain yield of rice varieties were discovered (Table 2). The highest grain yield (6.32 t ha^{-1}) was observed in V_3, which decreased slightly (9.91%) in V_2 but significantly (16.14%) in V_1. The treatments caused significant differences in rice grain yield. T_3 had the highest grain yield (6.66 t ha^{-1}) while T_2 and T_1 reduced significantly by 13.96 and 25.23 percent, respectively. The combining effects of rice varieties and application of Zn showed significant differences. The highest grain yield (6.82 t ha^{-1}) was observed in V_3T_3 and the lowest (4.56 t ha^{-1}) in V_1T_1 (Table 2).

3.9 Straw Yield (t ha^{-1}): In straw yield, Rice varieties exhibit non-significant differences (Table 2). The highest straw yield (8.17 t ha^{-1}) was observed in V_3 and the lowest (6.82 t ha^{-1}) in V_1. Significant differences were observed in straw yield due to the application of different doses of Zn fertilizer. The highest straw yield (8.91 t ha^{-1}) was observed in T_3, which reduced significantly by 17.62 % and 30.98 % in T_2 and T_1, respectively. Straw yield showed significant differences from

Table 2: Effect of zinc fertilization on yield contributing parameters and yield of boro rice

Variety	Panicle Length (cm)	Number of Grain panicle^{-1}	1000 Grain Weight (g)	Grain Yield (tha^{-1})	Straw Yield (tha^{-1})	Biological yield (tha^{-1})
V_1	19.77±0.29c	156.00±5.31	23.20±0.267	5.30±0.34b	6.82±0.49	12.12±0.81
V_2	20.18±0.29ab	161.19±5.44	22.87±0.29	5.75±0.34ab	7.42±0.55	13.16±0.87
V_3	20.61±0.23a	169.00±4.93	22.34±0.36	6.32±0.26a	8.17±0.51	14.94±0.75
Treatment						
T_1	19.51±0.18b	148.93±2.26c	22.94±0.36ab	4.98±0.28c	6.15±0.21c	11.14±0.48c
T_2	20.13±0.28b	161.48±5.22b	23.20±0.28a	5.73±0.30b	7.34±0.48b	13.07±0.78b
T_3	20.93±0.16a	175.78±3.91a	22.28±0.26b	6.66±0.132a	8.91±0.41a	15.57±0.52a
Interaction						
V_1T_1	19.22±0.25b	145.89±3.21b	23.02±0.69ab	4.56±0.31c	5.81±0.24b	10.38±0.55c
V_1T_2	19.38±0.23b	147.44±3.31b	23.53±0.14a	4.92±0.43bc	6.04±0.14b	10.95±0.56c
V_1T_3	20.73±0.44a	174.67±7.40a	23.05±0.52ab	6.42±0.34a	8.60±0.63a	15.02±0.97ab
V_2T_1	19.30±0.19b	146.11±2.99b	23.44±0.25bc	4.71±0.38bc	5.97±0.13b	10.68±0.51c
V_2T_2	20.22±0.46ab	161.67±7.88ab	23.16±0.60ab	5.80±0.47ab	7.26±0.70ab	13.06±1.17abc
V_2T_3	21.02±0.22a	175.78±7.97a	22.02±0.15ab	6.73±0.15a	9.02±0.87a	15.74±1.01a
V_3T_1	20.00±0.31ab	154.78±4.04b	22.35±0.84ab	5.67±0.56abc	6.68±0.47b	12.35±1.01bc
V_3T_2	20.81±0.43a	175.33±7.73a	22.91±0.66ab	6.48±0.35a	8.71±0.66a	15.18±1.00ab
V_3T_3	21.03±0.22a	176.89±7.99a	21.76±0.23b	6.82±0.17a	9.13±0.86a	15.95±1.02a
CV(%)	2.77	6.67	3.92	11.06	13.69	11.73

The mean followed by different letter(s) in a column differed significantly, CV= Co-efficient of variation, LS= Level of significant, DAT= Days After Transplanting, $V_{1=}$BRRI dhan28, $V_{2=}$ BRRI dhan29, $V_{3=}$BRRI dhan58, T_1= Deeped in Zinc solution just before transplanting, T_2= Foliar application of zinc at tillering stage , T_3= Foliar application of zinc at both tillering and flowering stage.

the interaction effects of rice varieties and Zn fertilizers. The highest straw yield (9.13 t ha^{-1}) was observed in V_3T_3 and the lowest (5.81 t ha^{-1}) was in V_1T_1 (Table 2).

3.10 Biological Yield (t ha^{-1}): Biological yield showed non-significant differences in case of rice varieties (Table 2). The highest biological yield (14.94 t ha^{-1}) was observed in V_3 and the lowest (12.12 t ha^{-1}) in V_1. There were significant differences in biological yield due to Zn fertilization. The highest biological yield (15.57 t ha^{-1}) was observed in T_3, which reduced significantly by 16.06 % and 28.45 % in T_2 and T_1, respectively. Interaction effects between the rice varieties and Zn fertilizations exhibit significant differences in case of biological yield. The highest biological yield (15.95 t ha^{-1}) was observed in V_3T_3 and the lowest (10.38 t ha^{-1}) in V_1T_1 (Table 2).

3.11 Harvest Index (%): In the case of rice varieties, the harvest index revealed no significant differences (Table 2). V_3 had the highest harvest index (43.85 percent) and V_2 had the lowest (43.81 percent). There were non-significant differences were observed as a result of different Zn fertilization. The highest harvest index (44.56 %) was observed in T_1 and the lowest (42.94 %) in T_3. Following interaction effects between rice varieties and different treatments, the harvest index of rice did not differ significantly. The highest harvest index (45.82 percent) was observed when V_3 was combined with T_1, and the lowest (42.72 percent) when V_3T_2 was used (Figure 1).

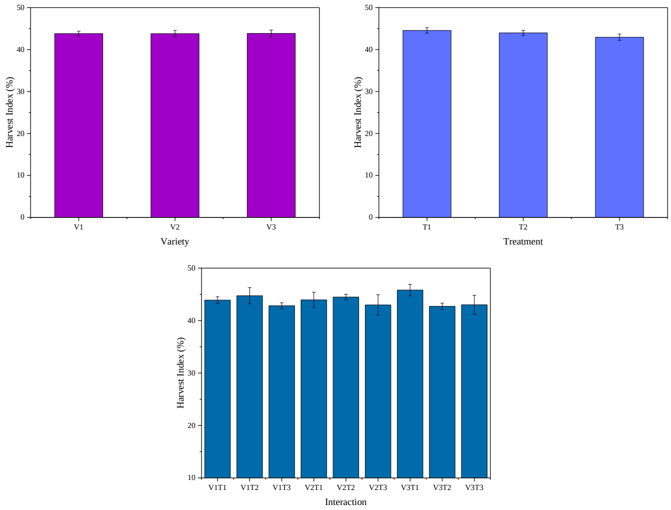

Figure 1: Effect of zinc fertilization on Harvest Index

4. Discussion

The observed fluctuations in growth parameters, tillering, panicle development, and yield parameters in response to different doses and application methods of Zinc (Zn) can be attributed to several underlying physiological and biochemical mechanisms. The increase in plant height with foliar application of Zn, particularly at both tillering and flowering stages, underscores Zn's crucial role in promoting cell division and elongation [12], [13]. This effect is primarily due to Zn acting as a cofactor for various enzymes involved in auxin synthesis [7], a plant hormone directly influencing cell expansion and elongation. Enhanced auxin activity facilitates greater internode elongation, resulting in taller plants. Additionally, Zn plays a critical role in maintaining membrane integrity and stabilizing protein structures [14], which are vital for sustained cell growth. Zn is essential for the synthesis of tryptophan [15], a precursor of auxin. Adequate Zn levels ensure sufficient auxin production, which, in turn, promotes the initiation and growth of tillers. Furthermore, Zn's involvement in protein synthesis and enzyme activation [16] supports robust growth and development of new tillers. The positive influence of Zn on panicle length and grain number per panicle can be attributed to its involvement in reproductive development. Zn is vital for the synthesis of ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) [16], [17], both of which are crucial for cell division and reproductive tissue development. Adequate Zn levels ensure proper formation and elongation of the panicle structure. Moreover, Zn's role in chlorophyll synthesis and photosynthesis ensures sufficient energy production for grain filling [6]. Zn is essential for the activation of numerous enzymes involved in carbohydrate [7], critical for energy production and storage. Enhanced carbohydrate metabolism ensures more assimilates are available for grain development. Zn also plays a pivotal role in nitrogen metabolism, enhancing protein synthesis [7] and overall plant growth. The increased straw yield indicates that Zn not only boosts grain production but also supports vegetative growth, contributing to higher total biomass. The timing and method of Zn application significantly influence its availability and effectiveness. Foliar applications at key growth stages, such as tillering and flowering, prove most beneficial for optimizing plant growth and yield. This method ensures that Zn is readily available during critical periods of growth, leading to improved physiological and biochemical responses. Thus, the strategic application of Zn can significantly enhance overall plant health and productivity, demonstrating its importance in agronomic practices.

5. Conclusion

This study reveals the profound impact of zinc (Zn) fertilization on the growth and yield of boro rice varieties cultivated under the subtropical climate of Rajshahi. The research demonstrates that the method and timing of Zn application are critical to optimizing rice production. Among the various treatments, foliar application of Zn at both the tillering and flowering stages consistently resulted in the most significant improvements in plant height, tiller number, panicle length, and grain yield. This suggests that Zn plays a pivotal role in several physiological processes, including cell division, elongation, and reproductive development. The variety BRRI dhan58, in particular, exhibited superior performance across most measured parameters, indicating its responsiveness to Zn fertilization. The positive effects observed in both grain and straw yield further emphasize Zn's importance in overall biomass production. These findings highlight the need for targeted Zn application as a key agronomic practice to enhance rice productivity, especially in regions with similar soil and climatic conditions. Future research should investigate the long-term effects of Zn fertilization on soil health and its interactions with other micronutrients. Expanding the study across different rice varieties and agro-ecological zones would help validate and generalize these findings for broader application.

Conflict of Interest

Authors have no conflict of interest on this article.

Authors' Contributions

Author-1 wrote the first draft of the manuscript, researched literature and conceived the study. Author-2 involved in protocol development, Author-3 is the corresponding author, was involved in protocol development gaining ethical approval, patient recruitment, and data analysis revised the final draft of the manuscript. Both 2nd & 3rd authors reviewed and edited the manuscript and approved the final version of the manuscript.

Acknowledgments

We thank Billal Hossain Momen, Md.Sakhawat Hossain, Md.Rashedur Rahman Tanvir, and the field members of the department of Agronomy and Agricultural Extension for their kind help during field experiments.

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