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Micronutrient Interactions in Wheat: Implications of Boron and Zinc Management in Acidic Soils of Terai Region of West Bengal, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The soils of the Terai region of West Bengal are generally acidic in nature and deficient in available boron (B) and zinc (Zn) leading to widespread micronutrient constraints in the region. This study investigated the interaction effects of B and Zn on wheat growth, nutrient concentration and uptake in this region. A pot experiment was conducted using a factorial Completely Randomized Design (CRD) with three levels each of

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B (0, 2 and 2.5 mg kg^{-1}) and Zn (0, 5 and 10 mg kg^{-1}). The experimental soil was acidic (pH 5.70) and deficient in available B and Zn which corroborates the typical micronutrient constraints of the region. Results revealed that B application significantly increased shoot dry matter yield, with maximum yield at 2.5 mg kg^{-1} B. Zinc application showed a less consistent response, though a higher dose (10 mg kg^{-1}) significantly improved yield. The combined application of B (2.5 mg kg^{-1}) and Zn (10 mg kg^{-1}) produced the highest biomass, indicating a positive interaction effect. B application significantly increased both B and Zn concentrations in plant tissues whereas Zn application reduced B concentration, indicating an antagonistic interaction at higher levels. However, Zn played a protective role by mitigating B toxicity and improving nutrient balance. Nutrient uptake data indicated substantial increases in both B and Zn uptake with combined application, particularly at higher levels. The findings demonstrate that balanced application of B and Zn enhances wheat productivity and nutrient use efficiency in acidic soils. The study highlights the importance of Zn–B stoichiometry in optimizing crop performance and suggests that appropriate micronutrient management strategies are essential for sustainable wheat production and biofortification in micronutrient-deficient regions.

Keywords: Wheat; biofortification; nutrient use efficiency; yield; nutrient uptake.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops contributing significantly to global food security. However, its productivity is decreasing due to the depletion of essential micronutrients in soils (Mandal et al., 2023). Among these, Zinc (Zn) and Boron (B) are two fundamental micronutrients for the growth and vitality of higher plants (Padbhushan & Kumar, 2015). B plays vital role in diverse physiological functions such as cell-wall structural stability, membrane integrity, sugar transport and reproductive development (Padbhushan & Kumar, 2017; Mandal et al., 2023). Similarly, Zn is a critical cofactor for numerous enzymes and is essential for crop health and yield (Mishra et al., 2025).

In India, the extensive cultivation of high-yielding varieties coupled with inadequate application of organic manures has led to the gradual depletion of soil micronutrient reserves. Recent studies show around 44.7% of Indian soils are deficient in B with states like West-Bengal showing high vulnerability (Shukla et al., 2021). The acidic Fluvisols of north-eastern Terai of West Bengal especially deficient where heavy rainfall leads to leaching of non-ionic B beyond the rhizosphere (Prasad et al., 2014). Approximately 40% of Indian soils are deficient in Zn with states like West Bengal showing high vulnerability (Shukla et al., 2016)

In recent years, scientists have shown growing concern over the complex yet crucial interaction between Zn and B as their balanced application can substantially improve wheat productivity by enhancing root development, nutrient uptake and reproductive growth (Shukla et al., 2019). Understanding the synergistic or antagonistic interaction between Zn and B is therefore imperative for developing balanced fertilization regimes in the soils of Coochbehar district.

Plant uptakes B and Zn are influenced by different transporters, which is important to understand movement and translocation of these nutrients. Plant uptakes Zn via ZIP transporters and B movement occur through BOR transporter facilitated by NIP5 channels. ZIP transporter, NIP5 and YSL2 have role in the mobilization of these nutrients from cortex to endodermis and then pericycle. Xylem loading of Zn and B takes place via HMA pumps and ZIP2, respectively. ZIP, YSL and YS/YSL transporters have role in movement and translocation of Zn and B from xylem to phloem. B accumulation in leaf occurs through transpiration pull. The leaf B concentration is directly related with the crop growth and development and therefore increasing leaf B concentration may increase the yield (Padbhushan & Kumar, 2015).

Previous research showed that soil and foliar applications of Zn and B can improve nutrient uptake and crop yield (Padbhushan & Kumar, 2014; Gao et al., 2024; Hossain et al., 2024). However, time is needed to judiciously synchronize management Zn and B, which is important for overcoming this problem. Balanced Zn and B nutrition improves cell wall integrity, supports photosynthate translocation, and improves reproductive processes such as pollen germination, flower retention, and seed development (Dubey and Pathak, 2024). In cereal-based systems like the rice–wheat cropping system, long-term cultivation without micronutrient replenishment has led to a significant decline in soil fertility (Meena et al., 2024). Despite these concerns, however, limited information is available regarding Zn-B interactions in acid soils and their impact on nutrient dynamics and crop productivity in the wheat crop. We hypothesized that Zn and B interacted may optimize the crop production in acid soil. This study provides new evidence on the effects of Zn and B applied wheat crop grown on micronutrient-deficient acid soil under controlled conditions. The outcomes of this finding will contribute to the development of region-specific micronutrient management strategies that support sustainable agriculture and long-term food security in one of the world's most vital agricultural regions. This study investigated the interaction effects of B and Zn on wheat growth, nutrient concentration and uptake in the acid soil.

2. Materials and Methods

The study was conducted in plastic pots (capacity: 5 kg soil) following a factorial Completely Randomized Design (CRD). The experiment comprised nine treatments with three levels each of boron (B) and zinc (Zn). B was applied at 0, 2 and 2.5 mg kg^{-1} (Güneş et al., 2000) while Zn was applied at 0, 5 and 10 mg kg^{-1} (Mishra et al., 2025). Prior to sowing, a uniform basal dose of nitrogen, phosphorus and potassium was applied to all pots at the rate of 120, 60 and 60 mg kg^{-1} soil, respectively. Each treatment was replicated three times.

Bulk soil from the Instructional Farm of Uttar Banga Krishi Viswavidyalaya (UBKV), Pundibari, Coochbehar (26°24′27″ N latitude, 89°22′59″ E longitude; 43 m above mean sea level) was collected. Initial soil physical and chemical analysis was done by following standard protocols as proposed by Black (1965), Jackson (1973) and McLean (1965). Each pot was filled with 5 kg of soil and applied with graded levels of B and Zn. The experimental site is located in the per-humid subtropical Terai region, falling under the Eastern Himalayan agro-climatic zone (Mandal et al., 2016).

Soil moisture content was maintained at 60 ± 5% of water holding capacity using demineralized water. Five to six pre-germinated wheat seeds were sown in each pot and after 10 days of emergence, the seedlings were thinned to three plants per pot. Soil moisture was maintained throughout the experimental period by periodic addition of demineralized water. Necessary intercultural operations, including weed control and plant protection measures were carried out uniformly as required.

The above-ground plant parts were harvested at the booting stage (45 days after sowing). The harvested samples were washed with demineralized water, oven-dried at 60°C for 48 hours and weighed to determine shoot dry matter yield. The dried plant samples were then ground using a stainless-steel mill for subsequent B and Zn analysis.

For B estimation, 1 g of plant sample was dry-ashed at 600°C for 1 hour. The ash was dissolved in 10 mL of 0.36 N H_2SO_4 and the volume was made up to 20 ml with the same acid, followed by filtration. B concentration was determined using the Azomethine-H method as described by Gaines and Mitchell (1979).

For Zn estimation, 0.25 g of plant sample was digested using a tri-acid mixture (HNO_3:H_2SO_4: $HClO_4$). After digestion and filtration, Zn concentration in the extract was determined using an Atomic Absorption Spectrophotometer following the procedure outlined by Steponeniene et al. (2003).

All experimental data were subjected to statistical analysis using the GenStat software package. The analysis was performed in accordance with the factorial Completely Randomized Design to evaluate the effects of B and Zn levels and their interactions.

3. Results and Discussion

The important soil physico-chemical parameters (pH, SOC, silt, clay, CEC and Available N, P, K, B and Zn) of the experimental soils were presented in Table 1. The data showed that soil was acidic, high organic matter, low nitrogen, medium phosphorus, low potassium and deficient in zinc and boron.

3.1 Shoot Dry Matter Yield

The application of both boron (B) and zinc (Zn) significantly influenced wheat shoot dry matter yield, with a strong interaction effect between the two nutrients (Table 2). Due to increasing levels of B, there was significant ($P<0.05$) increase in mean shoot dry matter yield from 3.49 g pot^{-1} at 0 ppm B to 4.20 g pot^{-1} at 2 mg B kg^{-1} and further to 5.16 g pot^{-1} at 2.5 mg B kg^{-1}. The B application enhanced biomass production due to its role in cell wall formation, carbohydrate transport and meristematic growth (Biswas et al., 2015, Sattar et al., 2023 and Reddy et al., 2023). Saha et al. (2025) reported similar influence of B on tomato crops and reported improvement in crop yield over control by applying B @ 2 mg kg^{-1}.

Table 1. Physical and chemical parameters of soil for the experimental pot culture

Parameter	Value
pH (soil:water ::1:2.5)	5.70
Total Organic carbon (%)	1.42
Sand (%)	62.31
Silt (%)	20.87
Clay (%)	16.82
CEC (Cmol (p+) Kg^{-1})	8.23
Available Nitrogen (mg kg^{-1})	113.03
Available Phosphorous (mg kg^{-1})	12.71
Available Potassium (mg kg^{-1})	114.9
Available Boron (mg kg^{-1})	0.05
Available Zinc (mg kg^{-1})	0.45

The effect of Zn application was comparatively less consistent. The mean shoot dry matter was 4.12 g pot^{-1} at 0 mg Zn kg^{-1}, decreased slightly to 3.94 g pot^{-1} at 5 mg Zn kg^{-1} and increased to 4.79 g pot^{-1} at 10 mg Zn kg^{-1}. The reduction of straw yield at 5 mg Zn kg^{-1} in comparison to 0 mg Zn kg^{-1} is non-significant, whereas the increase at 10 mg Zn kg^{-1} was significant ($P<0.05$). This suggests that moderate Zn levels may not be sufficient, but higher Zn enhances growth, possibly due to its involvement in enzyme activation and auxin synthesis. Shambhavi et al. (2020) reported similar influence of Zn on maize-wheat cropping system and reported improvement in crop yield over control by applying Zn @ 10 mg kg^{-1}.

The combined application of B @ 2.5 mg Kg^{-1} and Zn @ 10 mg Kg^{-1} had a significant impact on the overall dry matter yield of wheat. The interaction of Zn and B seems to have positive effect on the dry matter yield. Response on dry matter yield as a result of application of B @ 2.0 and 2.5 mg Kg^{-1} is recorded as 20% and 48.57% higher, respectively over control. These results are in conformity with a greenhouse experiment conducted by Hosseini (2006) which revealed that straw was more sensitive to excess B than the grain. Results indicated that B applied at levels greater than 2.5-5 mg kg^{-1} soil decreased grain and straw yields as the toxicity threshold for B is very narrow. Zn application at rate of 5 mg kg^{-1} failed to increase the mean shoot dry matter yields of wheat. But application of Zn @ 10 mg kg^{-1} resulted in significant increase in dry matter yield of wheat shoot by 16.50% over control. Added level B resulted in an overall significant increase in mean shoot dry matter yields of wheat plant.

Table 2. Effect of boron and zinc on shoots dry matter of wheat (g pot^{-1})

Zinc (mg kg^{-1}) / **Boron (mg kg^{-1})**	**0.0**	**5.0**	**10.0**	**Mean**
0.0	3.42	3.76	3.31	3.49
2.0	4.48	3.06	5.05	4.20
2.5	4.46	4.99	6.03	5.16
Mean	4.12	3.94	4.79	
	Boron	Zinc	Boron × Zinc	
$LSD_{0.05}$	0.27	0.27	0.48	
SEm±	0.13	0.13	0.22	

Note: LSD-Least square difference, SEm-Mean standard error

3.2 Zn and B Concentration (mg kg^{-1}) in Shoots

Data showed that Zn and B treatments significantly ($P<0.05$) affected the Zn content of wheat shoot over the control during the years of experiment (Table 3). The increase in Zn concentration was significant ($P<0.05$) at level 10 mg kg^{-1} by 13.85% over control. Thus, application of Zn in soils resulted in enhanced mean Zn content of wheat shoots. The mean effect of B on Zn content was more significant as results showed an increase of 48.21% and 76.93% in comparison to control when B was applied at rates 2 and 2.5 mg kg^{-1} (Table 3). When Zn is added @ 10 mg kg^{-1}, B levels decrease substantially. The data presented in Table 2 revealed that the application of B in different doses (0, 2 and 2.5 mg kg^{-1}) resulted in significant increase in B concentration of the shoot of wheat. The increase in concentration was 650% and 1116% over the control when the B is applied @ 2 and 2.5 mg kg^{-1} of soils.

There is substantial decrement in B levels when Zn is applied, the effect being prominent at dosage of B @ 2.5 mg kg^{-1}. The decreased proportions are 8.21% and 19.84% when Zn is applied @ 5 mg kg^{-1} and 10 mg kg^{-1}, respectively. Similar trends have been reported by Singh et al. (1990) and Hosseini (2006) indicating that Zn lowered content of B in grains up to 14.3% against the control (Table 2). Results are in conformity with that already reported by Singh et al. (1990) that the concentration of Zn in shoot of wheat have improved at all level of B, but increase is significant when Zn is applied @ 10 mg kg^{-1} at all levels of B (Table 3).

Table 3. Effect of boron and zinc on wheat shoot zinc concentration (mg Kg^{-1})

Zinc (mg kg^{-1}) / Boron (mg kg^{-1})	0.0	5.0	10.0	Mean
0.0	13.15	14.28	16.10	14.51
2.0	20.62	21.24	22.68	21.51
2.5	24.71	24.55	27.82	25.69
Mean	19.49	20.02	22.20	
	Boron	Zinc	Boron × Zinc	
$LSD_{0.05}$	0.72	0.72	1.25	
SEm±	0.34	0.34	0.59	

3.3 Zn and B Uptake in Shoots

The effect of additional B application on uptake of B is significant at all levels of B. There is increase of 776.7% and 1291% Boron uptake over control which shows the significant effect (Table 4). Padbhushan and Kumar (2015) reported similar influence of B on increasing B uptake by shoots of the crop. Addition of Zn @ 5 mg kg^{-1} to soils significantly decreased B uptake by 13.45% in comparison to control. At higher level of application, i.e., Zn @ 10 mg kg^{-1} mean B uptake improved slightly. Scientists have reported that the Zn provided a protective mechanism against excessive uptake of B i.e., it may play a protective role in the absorption and translocation of B (Padbhushan et al., 2019). Data reveals that the combined effect of B and Zn application resulted in decrease of B uptake in soils with no B and all three doses of Zn. Consequently, soils with two levels of B (2 and 2.5 m kg^{-1}) showed significant increase in B uptake by wheat shoots compared to soils with zero added boron. But this increase in uptake at a level of B i.e., 2.5 mg kg^{-1}, is significant only when there is application of 10 mg kg^{-1} Zn in soil. There is significant decrease in B uptake when B and Zn are applied @ 2 mg kg^{-1} and 5 mg kg^{-1} in soil.

Table 4. Effect of boron and zinc on wheat shoot boron uptake (mg pot^{-1})

Zinc (mg kg^{-1}) / Boron (mg kg^{-1})	0.0	5.0	10.0	Mean
0.0	5.74	3.91	3.98	4.54
2.0	43.31	29.61	46.74	39.88
2.5	61.36	62.02	66.52	63.30
Mean	36.80	31.85	39.08	
	Boron	Zinc	Boron × Zinc	
$LSD_{0.05}$	3.47	3.47	6.01	
SEm±	1.65	1.65	2.86	

There is depressive effect of Zn on B is concentration of wheat shoot (Table 5). The toxicity of B is reduced by Zn at higher levels of application (10 mg kg^{-1}) and as a result significant improvement in dry matter yield and uptake of B by wheat shoot is observed. Similar trend in effect of B on Zn uptake is observed (Table 5). Mean effect of B on Zn uptake is highly significant at all the doses of B. Effect of application of Zn @ 5 mg kg^{-1} is depressive in case of Zn uptake, but there is significant increase (35.45% more than control) in Zn uptake at the higher level of Zn application (10 mg kg^{-1}). The effect of B and Zn remain the same irrespective of the crop grown. According to the results of a pot experiment with maize, grown on Zn-deficient soil of Turkey, it was observed that dry matter yield of maize decreased significantly with B application in Zn-deficient soil. N, P, K, Cu, Zn and Mn concentration of plant increased with B and Zn application (Adloglu & Adloglu, 2006). Gunes et al. (2000) reported that in a greenhouse experiment involving four levels of B (0, 5, 10 and 20 mg B kg^{-1}) and 3 levels of Zn (0, 10 and 20 mg Zn kg^{-1}) conducted on tomato plants, B-toxicity symptoms occurred at 10 to 20 $mg.kg^{-1}$ B levels. These symptoms were similar to those grown with applied Zn. Fresh and dry weight of plants clearly decreased with applied B. However, Zn treatments partially depressed the inhibited effect of B on the growth. Increased levels of B increased the concentration of B in plant tissues and to a greater extent in the absence of applied Zn and B treatments caused an increase in Zn concentration in the plant. Thus, Zn is necessary for root cell membrane integrity and therefore, it prevents excessive P uptake by roots and transport P from roots to leaves. As a biochemical and physiological function, B resembles phosphate (Begrmann, 1992). Similarly, Zn may also have possibly a protective role in the absorption and translocation of boron.

Table 5. Effect of boron and zinc on wheat shoot zinc uptake (mg pot^{-1})

Zinc (mg kg^{-1}) / Boron (mg kg^{-1})	0.0	5.0	10.0	Mean
0.0	45.01	53.77	53.29	50.69
2.0	92.37	65.15	114.58	90.70
2.5	110.41	122.82	167.77	133.67
Mean	82.59	80.58	111.88	
	Boron	Zinc	Boron × Zinc	
$LSD_{0.05}$	8.14	8.14	14.10	
SEm±	3.87	3.87	6.71	

4. Conclusion

Based on the experimental findings, it is concluded that the individual application of boron (B) significantly enhanced dry matter yield with an increase of up to 48.57% over the control. In contrast, zinc (Zn) exhibited a significant positive effect only at a higher application rate of 10 mg kg^{-1} soil indicating the greater Zn requirement for achieving optimum crop response. The study further revealed that elevated Zn levels may play a protective role against B toxicity by acting as a buffering agent, thereby sustaining plant growth and allowing for the yield increase. Conversely, there is a clear synergistic relationship where B facilitates in increasing Zn concentration and uptake. Optimal wheat growth and nutrient balance are achieved at higher Zn concentration (10 mg kg^{-1}) when B levels are also elevated. Therefore, this study concludes a balanced Zn-B stoichiometry is essential for optimizing wheat biofortification, improving grain quality and ensuring sustainable productivity.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

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

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