

## Optimizing Maize (*Zea Mays* L.) Productivity Through Zinc and Boron Application in Red and Lateritic Soils of West Bengal

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### Abstract

A two-year field experiment (2021–22 and 2022–23) was conducted at the Agricultural Farm of Palli Siksha Bhavana, Visva-Bharati, Sriniketan, West Bengal, to evaluate the effect of zinc (Zn) and boron (B) application on growth, yield, and grain quality of maize (*Zea mays* L.) grown in red and lateritic soils. The experiment was laid out in a randomized block design with twelve treatments and three replications, comprising RDF ( $N_{90}P_{60}K_{60}$  kg ha<sup>-1</sup>) alone, soil application of Zn (5 and 10 kg ha<sup>-1</sup>), B (1 and 2 kg ha<sup>-1</sup>), their combinations, and foliar application (ZnSO<sub>4</sub> @ 0.5% and Borax @ 0.1%). Pooled analysis revealed significant improvement in growth, yield, and quality parameters due to micronutrient application. Treatment T<sub>6</sub> (RDF + Zn 5 kg ha<sup>-1</sup> + B 1 kg ha<sup>-1</sup>) recorded superior vegetative growth with maximum plant height (140.67 cm at 30 DAS and 234.83 cm at 60 DAS) and highest dry matter accumulation (118.43 g plant<sup>-1</sup> at 60 DAS). Among yield parameters, T<sub>8</sub> (RDF + Zn 10 kg ha<sup>-1</sup> + B 1 kg ha<sup>-1</sup>) recorded the highest pooled grain yield (4.78 t ha<sup>-1</sup>), along with improved cob traits. Grain quality was also significantly enhanced, with maximum starch (6.28%), protein (7.21%), and oil content (3.64%) observed under combined Zn and B treatments, particularly T<sub>8</sub> and T<sub>9</sub>. The results demonstrate that integrated soil application of zinc and boron significantly improves maize productivity and grain quality in micronutrient-deficient red and lateritic soils of Eastern India.

**Keywords:** Maize, Zinc, Boron, Micronutrient application, Growth, Yield, Quality parameters

## Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, contributing significantly to food security, animal feed, and a wide range of industrial products such as starch, ethanol, and biofuel [1]. In India, maize ranks as the third most important cereal crop after rice and wheat, contributing approximately 9% to the national food basket, and is widely cultivated due to its high yield potential and adaptability across diverse Agro-climatic regions (ICAR, 2022). The cultivation of maize has expanded rapidly in recent years, driven by increasing demand from the poultry feed, food processing, and bio-industrial sectors [2]. Despite its importance, maize productivity in several regions of India remains below its genetic potential, largely due to sub-optimal crop management practices, poor soil fertility, and imbalanced nutrient [3, 4]. In the red and lateritic soils of West Bengal, maize cultivation is particularly constrained by low organic matter content, soil acidity, and widespread micronutrient deficiencies, especially zinc and boron, which adversely affect crop growth, yield, and grain quality [5, 6]. Addressing these soil fertility constraints through balanced and integrated nutrient management is therefore essential for improving maize productivity in such ecologically fragile regions. Zn and B play pivotal roles in enzymatic functions, chlorophyll synthesis, and reproductive development, ultimately influencing maize productivity. Widespread deficiencies of Zn and B, among other micro nutrients, significantly impair plant growth, yield, nutrient use efficiency, and nutritional quality of produce, leading to stunted growth and poor kernel formation in maize. Due to high-yielding cultivars, decreased organic inputs, and uneven fertilization, multi-micro nutrient deficits are becoming more common in India. To address this, balanced nutrient management strategies incorporating zinc and boron supplementation have been explored to enhance maize performance. However, the efficiency of these micro nutrients varies depending on their dosage, method of application (soil or foliar), and interactions with macro nutrient fertilization. West Bengal's lateritic and red soils, which are marked by high acidity, low fertility, and low organic matter content, present major obstacles to sustainable agricultural production. These soils frequently have natural deficiencies in minerals, especially boron, and zinc, which are essential

for growing maize. Limited use of organic inputs, erosion, and intense cropping all contribute to the deficits. Due to its sensitivity to micro nutrients and its high need for zinc and boron throughout crucial growth phases such as early vegetative development, tasselling, and grain filling, maize experiences significant production losses in these circumstances. According to studies, applying borax and zinc sulphate to maize cultivated on red and lateritic soils can greatly increase plant growth parameters, chlorophyll content, and grain output. Therefore, this field study was designed to evaluate the role of Zn and B application with different methods in improving productivity of maize grown under the Agro Climatic condition of West Bengal. The experiment, structured as A Randomized Block Design (RBD) with twelve treatment combinations, aimed to identify the optimal treatment strategy that maximizes maize productivity. By analysing key agronomic parameters such as plant height, chlorophyll content, cob weight, and grain yield, this research provides insights into effective micro nutrient management practices for improving maize cultivation in red and lateritic soils.

## Materials and Method

### Experimental Site

The experiment was conducted at the agricultural farm of Palli Siksha Bhavana, Visva-Bharati, Sriniketan, West Bengal, during the two kharif season of 2021–2022 (July to September) and 2022-2023 (July to September), in red and lateritic soils that are typically deficient in essential micro nutrients like zinc (Zn) and boron (B). The experimental site is characterized by a silt loam soil texture, which is generally known for its moderate water-holding capacity and good aeration properties, making it suitable for agricultural experimentation. Prior to the sowing of the first crop, a composite soil sample was systematically collected from the upper 0–15 cm layer of the soil across the experimental field to ensure representativeness. This initial soil sample was subjected to a comprehensive analysis to determine its important physical and chemical characteristics, which are critical for understanding the baseline fertility status and guiding subsequent nutrient management practices. The salient results of the soil analysis, along with the standard methods and procedures employed for each parameter, are

systematically presented. The initial analysis of the soil at the experimental site revealed that the soil pH was 6.1, indicating a moderately acidic condition. The electrical conductivity (EC) measured at 25°C was 0.09 dS/m, indicating a non-saline soil. The organic carbon content was found to be 0.29%, classifying it as low, which indicates poor organic matter status. The soil available N was 171.42 kg ha<sup>-1</sup>, which is rated as low, while Available P was 16.40 kg ha<sup>-1</sup> and available K was 183.31 kg ha<sup>-1</sup>, also rated as medium. The available Zn was 0.52 kg ha<sup>-1</sup> and boron B was 0.09 kg ha<sup>-1</sup>, both of which are categorized as low.

### Experimental Details

A randomized block design (RBD) with twelve treatment combinations and three replications was employed to evaluate the impact of different application rates and methods of zinc and boron on maize (*Zea mays* L.) growth and yield. The experimental treatments included a recommended dose of fertilizers (RDF) along with varying levels of zinc and boron applied either through soil incorporation or foliar application. The twelve treatments were: T<sub>1</sub>: RDF (N<sub>90</sub> + P<sub>60</sub> + K<sub>60</sub> kg ha<sup>-1</sup>), T<sub>2</sub>: RDF + ZnSO<sub>4</sub> (5 kg ha<sup>-1</sup> Zn), T<sub>3</sub>: RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn), T<sub>4</sub>: RDF + Borax (1 kg ha<sup>-1</sup> B), T<sub>5</sub>: RDF + Borax (2 kg ha<sup>-1</sup> B), T<sub>6</sub>: RDF + ZnSO<sub>4</sub> (5 kg ha<sup>-1</sup> Zn) + Borax (1 kg ha<sup>-1</sup> B), T<sub>7</sub>: RDF + ZnSO<sub>4</sub> (5 kg ha<sup>-1</sup> Zn) + Borax (2 kg ha<sup>-1</sup> B), T<sub>8</sub>: RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn) + Borax (1 kg ha<sup>-1</sup> B), T<sub>9</sub>: RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn) + Borax (2 kg ha<sup>-1</sup> B), T<sub>10</sub>: RDF + foliar application of ZnSO<sub>4</sub> @ 0.5%, T<sub>11</sub>: RDF + foliar application of Borax @ 0.1%, T<sub>12</sub>: RDF + foliar application of ZnSO<sub>4</sub> @ 0.5% + Borax @ 0.1%. The rates of Zn and B are expressed on an elemental basis. Standard agronomic practices were followed, where the field was ploughed and levelled before sowing, and seeds were sown at a spacing of 60 cm × 25 cm to ensure proper plant density. The recommended basal dose of N: P<sub>2</sub>O<sub>5</sub>: K<sub>2</sub>O (90:60:60 kg/ha) was applied, and zinc and boron treatments were administered according to the designated application method. Proper irrigation and weed management practices were followed throughout the crop cycle to ensure optimal growth.

### Soil Sampling and Analysis

Composite soil samples were collected randomly from the experimental site at a depth of 0–15 cm before sowing, air-dried, powdered, and analysed for various soil properties. Soil pH and electrical conductivity were determined as per the method suggested by [7], organic carbon content was analysed using the wet digestion method of Walkley and Black (1934), available nitrogen (N) was estimated using the Kjeldahl distillation process (Subbiah & Asija, 1956), available phosphorus (P) was determined by Bray's No.1 method [21], and ammonium acetate (CH<sub>3</sub>COONH<sub>4</sub>) extraction was used for available potassium (K) determination, followed by flame photometric analysis [7]. The DTPA extraction method [8] was employed to estimate plant-available Zn content using an atomic absorption spectrophotometer (AAS), while hot water extraction was used for boron estimation [9]. Growth parameters including plant height, number of branches, and chlorophyll content were recorded at 30-day intervals until harvest from five randomly selected and tagged plants. Chlorophyll a, chlorophyll b, and total chlorophyll were analysed following the procedure given by [10]. Yield and its related attributes, such as total grain yield (tons/ha), cob weight, cob length (mm), cob width (mm), number of cobs per plant, were recorded at harvest. Quality parameters including protein, carbohydrates, oil content, and starch content were estimated from maize grains as per standard protocols.

### Statistical Analysis

Statistical analysis of the experimental data was performed using analysis of variance (ANOVA) appropriate for a Randomized Block Design (RBD), considering treatments as fixed effects. For the two-year study, year × treatment interactions were tested to evaluate seasonal variation in treatment response. Since the interaction effects were found to be non-significant for most parameters, pooled analysis over years was carried out. Treatment means were compared using the standard error of the mean (SEm) and the least significant difference (LSD) test at the 5% level of significance ( $\alpha = 0.05$ ) following the procedure described by [11]. All statistical analyses were conducted using IBM SPSS Statistics (Version 2023).

## Result

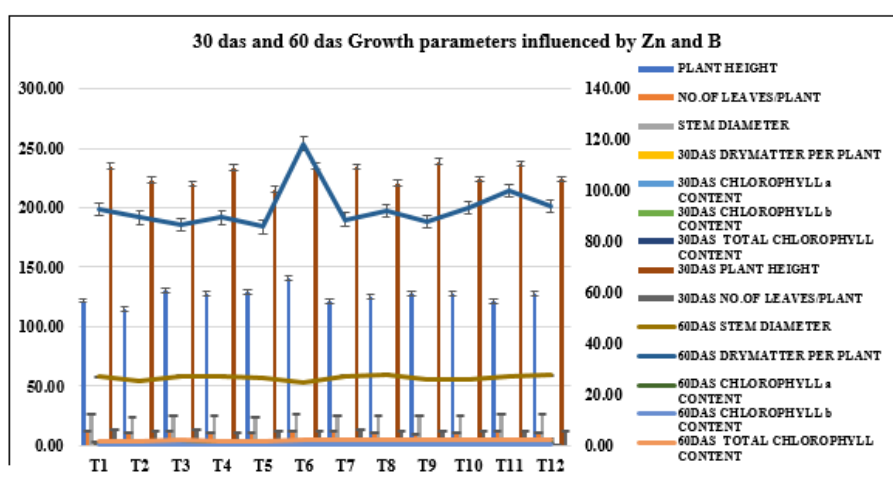
### Growth Attributes

Pooled data over two consecutive seasons revealed significant variation in maize growth attributes due to different zinc and boron treatments. At 30 days after sowing (DAS), Treatment T<sub>6</sub> (RDF + ZnSO<sub>4</sub> 5 kg ha<sup>-1</sup> Zn + Borax 1 kg ha<sup>-1</sup> B) recorded the tallest plants (140.67 cm), thickest stem diameter (27.26 mm), and higher leaf number (12.50 leaves plant<sup>-1</sup>), indicating superior early vegetative vigour. T<sub>1</sub> (RDF alone) recorded the maximum number of leaves (12.83 leaves plant<sup>-1</sup>), while T<sub>3</sub> (RDF + ZnSO<sub>4</sub> 10 kg ha<sup>-1</sup> Zn) achieved the highest dry matter accumulation (4.93 g plant<sup>-1</sup>). The highest chlorophyll content at this stage was observed in T<sub>8</sub> (RDF + ZnSO<sub>4</sub> 10 kg ha<sup>-1</sup> Zn + Borax 1 kg ha<sup>-1</sup> B) with 2.05 mg g<sup>-1</sup>, followed by T<sub>6</sub> and T<sub>7</sub>, indicating improved photosynthetic activity due to balanced micronu-

trient application.

By 60 DAS, all parameters improved markedly. T<sub>6</sub> again recorded higher dry matter accumulation (118.43 g plant<sup>-1</sup>), confirming the cumulative effect of combined soil-applied Zn and B. T<sub>9</sub> recorded the highest plant height (238.83 cm), while T<sub>8</sub> recorded the highest stem diameter (27.94 mm). T<sub>3</sub> recorded the highest number of leaves (14.22 leaves plant<sup>-1</sup>), followed by T<sub>7</sub> and T<sub>1</sub>. The highest total chlorophyll content was observed under T<sub>12</sub> (2.65 mg g<sup>-1</sup>) followed by T<sub>9</sub> and T<sub>8</sub>, indicating improved photosynthetic efficiency under micronutrient application.

Overall, treatments such as T<sub>6</sub>, T<sub>8</sub>, T<sub>9</sub>, and T<sub>12</sub> consistently performed better than others in key growth parameters, highlighting the importance of integrated micronutrient management-particularly the soil application of zinc and boron or their foliar combinations-for maximizing maize vegetative development under red and lateritic soils.



**Figure 1:** Growth Parameters as Influenced by Zinc and Boron Fertilization

T1: N90+P60+K60 RDF; T2: RDF+ ZnSO<sub>4</sub> (5kg/ha, Zn); T3: RDF+ ZnSO<sub>4</sub> (10kg/ha, Zn); T4: RDF+Borax (1 kg/ha, B); T5: RDF+Borax (2 kg/ha, B); T6: RDF + ZnSO<sub>4</sub> (5kg/ha, Zn) + Borax (1kg/ha, B); T7: RDF+ ZnSO<sub>4</sub> (5 kg/ha, Zn) + Borax (2 kg/ha, B); T8: RDF + ZnSO<sub>4</sub> (10 kg/ha, Zn) + Borax (1kg/ha, B); T9: RDF+ ZnSO<sub>4</sub> (10kg/ha, Zn) +Borax (2 kg/ha, B); T10: RDF + Foliar Application of ZnSO<sub>4</sub> @ 0.5%; T11: RDF + Foliar Application of Borax @ 0.1%; T12: RDF + Foliar Application of ZnSO<sub>4</sub> @ 0.5% + Foliar Application of Borax @ 0.1%

### Yield and Yield Attributes

The pooled mean data revealed notable and statistically significant variation in grain yield and cob morphological traits across the different treatments. Grain yield exhibited a wide range among treatments, reflecting the influence

of zinc and boron fertilization. During 2021–22, grain yield varied from 1.81 t ha<sup>-1</sup> (T<sub>4</sub>) to 3.16 t ha<sup>-1</sup> (T<sub>8</sub>), whereas in 2022–23, it ranged from 2.00 t ha<sup>-1</sup> (T<sub>10</sub>) to 3.23 t ha<sup>-1</sup> (T<sub>8</sub>). Based on pooled analysis, the highest grain yield (4.78 t ha<sup>-1</sup>) was recorded in T<sub>8</sub> (RDF + ZnSO<sub>4</sub> 10 kg ha<sup>-1</sup> Zn + Bo-

max 1 kg ha<sup>-1</sup> B), followed by T<sub>5</sub> (3.66 t ha<sup>-1</sup>), T<sub>7</sub> (3.66 t ha<sup>-1</sup>), T<sub>12</sub> (3.65 t ha<sup>-1</sup>) and T<sub>9</sub> (3.63 t ha<sup>-1</sup>), indicating the beneficial effect of combined zinc and boron application on maize productivity. The lowest pooled grain yield (2.86 t ha<sup>-1</sup>) was recorded under T<sub>4</sub> (RDF + Borax 1 kg ha<sup>-1</sup> B). The critical difference (CD) value for pooled grain yield was 1.44 t ha<sup>-1</sup>, confirming that the differences among treatments were statistically significant.

Cob weight also showed considerable variation across treatments. In 2021–22, cob weight ranged from 190.21 g (T<sub>6</sub>) to 289.70 g (T<sub>10</sub>), while in 2022–23 it ranged from 210.21 g (T<sub>6</sub>) to 271.81 g (T<sub>9</sub>). Based on pooled data, the highest cob weight (416.22 g) was recorded under T<sub>10</sub> (RDF + foliar application of ZnSO<sub>4</sub> @ 0.5%), followed by T<sub>3</sub> (410.40 g) and T<sub>9</sub> (407.72 g). The lowest pooled cob weight (295.32 g) was observed in T<sub>6</sub>. The CD value for pooled cob weight (80.11 g) indicated significant treatment effects on cob development.

Cob diameter also varied significantly among treatments. The pooled values ranged from 62.21 mm in T<sub>4</sub> to 74.05 mm in T<sub>7</sub>, indicating better cob development under

integrated micronutrient treatments. Treatments T<sub>7</sub>, T<sub>10</sub>, and T<sub>11</sub> recorded comparatively higher cob diameter values, reflecting improved reproductive growth and kernel accommodation.

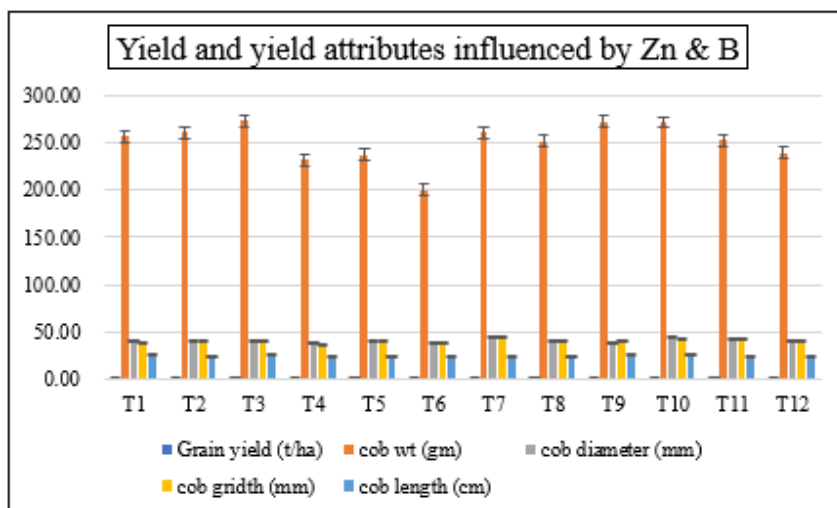
Similarly, cob girth showed considerable variation among treatments. The pooled cob girth ranged from 52.62 mm in T<sub>4</sub> to 64.04 mm in T<sub>7</sub>, with treatments T<sub>7</sub>, T<sub>10</sub>, and T<sub>11</sub> exhibiting higher girth values, suggesting enhanced cob robustness under micronutrient fertilization.

Cob length also differed among treatments. The pooled values ranged from 36.68 cm in T<sub>12</sub> to 41.05 cm in T<sub>3</sub>. Treatments T<sub>3</sub>, T<sub>9</sub>, and T<sub>10</sub> recorded relatively longer cobs compared to other treatments, indicating favorable conditions for cob development under these nutrient management practices.

Overall, treatments T<sub>8</sub>, T<sub>7</sub>, T<sub>9</sub>, T<sub>5</sub>, and T<sub>12</sub> showed superior performance in terms of grain yield and cob characteristics, demonstrating that the combined application of zinc and boron along with RDF significantly improves maize productivity in red and lateritic soils.

**Table 1:** Yield and Yield Attributes of Maize Crop as Influenced by Zinc and Boron Fertilization

Yield and yield attributes of maize crop as influenced by Zn and B fertilization															
Treatments	Grain yield (t/ha)			Cob wt. (gm)			Cob diameter (mm)			Cob girth (mm)			Cob length (cm)		
	2021-22	2022-23	POOLED	2021-22	2022-23	POOLED	2021-22	2022-23	POOLED	2021-22	2022-23	POOLED	2021-22	2022-23	POOLED
T1	1.87	2.12	2.93	268.31	244.98	390.8	47.49	32.62	63.8	33.29	45.49	56.03	26.33	25.6	39.13
T2	2.05	2.38	3.24	259.31	262.64	390.63	49.96	30.88	65.4	29.55	50.62	54.86	25.89	25.45	38.61
T3	1.86	2.19	2.95	274.82	271.15	410.4	51.43	32.06	67.46	31.06	50.76	56.44	27.33	27.44	41.05
T4	1.81	2.11	2.86	231.52	231.52	347.28	46.76	30.9	62.21	29.9	45.42	52.62	24.44	24.78	36.83
T5	2.11	3.11	3.66	234.86	238.2	353.96	49.83	32.82	66.24	31.82	50.15	56.9	26	25.67	38.83
T6	1.91	2.15	2.99	190.21	210.21	295.32	47.99	28.94	62.46	29.61	48.66	53.94	25.22	26.22	38.33
T7	2.44	2.44	3.66	267.45	254.12	394.51	56.38	35.35	74.05	36.35	55.38	64.04	24.88	24.55	37.16
T8	3.16	3.23	4.78	245.04	258.38	374.23	49.45	33.16	66.03	33.49	48.45	57.72	25.78	25.78	38.67
T9	2.4	2.47	3.63	271.81	271.81	407.72	48.57	30.57	63.86	33.57	48.91	58.03	26	26.13	39.06
T10	2.2	2	3.21	289.7	253.03	416.22	51.38	37.38	70.07	37.71	49.38	62.4	26.33	26.33	39.5
T11	2.04	2.38	3.23	251.94	251.94	377.92	52.34	35.01	69.85	34.34	52.01	60.35	25.78	25.44	38.5
T12	2.41	2.47	3.65	240.42	237.09	358.96	50.39	33.36	67.07	33.69	49.72	58.55	24.44	24.46	36.68
CD	1.01	0.86	1.44	55.85	48.53	80.11	6.66	6.74	10.04	6.66	7.94	10.63	3.11	2.36	4.29
SEm (±)	0.23	0.2	0.34	13.03	11.32	18.69	1.55	1.57	2.34	1.55	1.85	2.48	0.72	0.55	1
CV	18.6	14.34	25.77	8.95	7.88	12.89	8.19	8.32	12.35	8.19	6.47	11.43	4.88	3.71	6.74



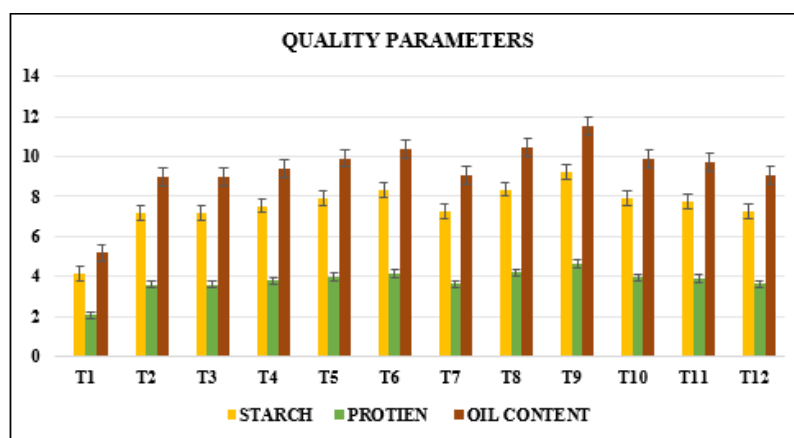
**Figure 2:** Yield and Yield Attributes of Maize Crop as Influenced by Zinc and Boron Fertilization.

T1: N90+P60+K60 RDF; T2: RDF+ ZnSO<sub>4</sub> (5kg/ha, Zn); T3: RDF+ ZnSO<sub>4</sub> (10kg/ha, Zn); T4: RDF+Borax (1 kg/ha, B); T5: RDF+Borax (2 kg/ha, B); T6: RDF + ZnSO<sub>4</sub> (5kg/ha, Zn) + Borax (1kg/ha, B); T7: RDF+ ZnSO<sub>4</sub> (5 kg/ha, Zn) + Borax (2 kg/ha, B); T8: RDF + ZnSO<sub>4</sub> (10 kg/ha, Zn) + Borax (1kg/ha, B); T9: RDF+ ZnSO<sub>4</sub> (10kg/ha, Zn) +Borax (2 kg/ha, B); T10: RDF + Foliar Application of ZnSO<sub>4</sub> @0.5%; T11: RDF + Foliar Application of Borax @0.1%; T12: RDF + Foliar Application of ZnSO<sub>4</sub> @0.5% + Foliar Application of Borax @0.1%

### Quality Parameters

The pooled data indicated that grain quality parameters of maize were significantly influenced by zinc and boron application. Starch content varied considerably among treatments, ranging from 2.82% in T<sub>1</sub> (RDF alone) to 6.28% in T<sub>9</sub> (RDF + Zn 10 kg ha<sup>-1</sup> + B 2 kg ha<sup>-1</sup>), with T<sub>8</sub> and T<sub>6</sub> also recording comparatively higher starch accumulation. Grain protein content ranged approximately from 5.12% to 7.21%, with higher values observed under treatments receiving either sole or combined micronutrient

application, particularly T<sub>2</sub>, T<sub>5</sub>, T<sub>6</sub>, and T<sub>9</sub>, compared to RDF alone. Oil content showed relatively narrower variation, ranging from about 3.07% to 3.64% with maximum values recorded under T<sub>8</sub> and T<sub>9</sub>, followed by T<sub>12</sub>. Total carbohydrate content also showed slight improvement under combined Zn and B treatments compared to control. Overall, treatments involving integrated soil application of zinc and boron, especially T<sub>8</sub> and T<sub>9</sub>, consistently enhanced starch, protein, and oil contents, indicating the positive influence of balanced micronutrient management on maize grain quality.



**Figure 3:** Effect of Zn and B application on Quality Parameters of Maize.

T1: N90+P60+K60 RDF; T2: RDF+ ZnSO<sub>4</sub> (5kg/ha, Zn); T3: RDF+ ZnSO<sub>4</sub> (10kg/ha, Zn); T4: RDF+Borax (1 kg/ha, B); T5: RDF+Borax (2 kg/ha, B); T6: RDF + ZnSO<sub>4</sub> (5kg/ha, Zn) + Borax (1kg/ha, B); T7: RDF+ ZnSO<sub>4</sub> (5 kg/ha, Zn) + Borax (2 kg/ha, B); T8: RDF + ZnSO<sub>4</sub> (10 kg/ha, Zn) + Borax (1kg/ha, B); T9: RDF+ ZnSO<sub>4</sub> (10kg/ha, Zn) +Borax (2 kg/ha, B); T10: RDF + Foliar Application of ZnSO<sub>4</sub> @0.5%; T11: RDF + Foliar Application of Borax @0.1%; T12: RDF + Foliar Application of ZnSO<sub>4</sub> @0.5% + Foliar Application of Borax @0.1%

## Discussion

### Influence of Zn and B application on Growth Attributes and Chlorophyll Content

The pooled data over two consecutive growing seasons clearly demonstrated that micronutrient treatments significantly influenced maize growth parameters, including plant height, number of leaves, stem diameter, dry matter accumulation, and chlorophyll content at both 30 and 60 DAS. At 30 DAS, plant height varied from 114.50 cm (T<sub>2</sub>: RDF + ZnSO<sub>4</sub> 5 kg ha<sup>-1</sup> Zn) to 140.67 cm (T<sub>6</sub>: RDF + ZnSO<sub>4</sub> 5 kg ha<sup>-1</sup> Zn + Borax 1 kg ha<sup>-1</sup> B). The enhanced height observed in combined Zn and B treatments may be associated with improved nutrient uptake and synergistic effects on metabolic activity that regulate cell division and elongation.

Likewise, the number of leaves per plant ranged between 10.67 and 12.83, with treatments such as T<sub>1</sub> (RDF only), T<sub>3</sub> (RDF + ZnSO<sub>4</sub> 10 kg ha<sup>-1</sup> Zn), and T<sub>6</sub> showing relatively higher values, suggesting better leaf initiation and canopy development.

Stem diameter at 30 DAS ranged from 23.94 mm to 27.26 mm, with the thickest stems recorded in T<sub>6</sub>, suggesting structural stability and enhanced vascular development due to combined micronutrient effects. Dry matter per plant ranged from 4.23 g to 4.93 g, reflecting efficient photosynthate production and allocation supported by adequate Zn nutrition. Chlorophyll content also displayed variation (1.22–2.05 mg g<sup>-1</sup> fresh weight), with treatments such as T<sub>8</sub>, T<sub>6</sub>, and T<sub>7</sub> showing higher levels, indicating enhanced photosynthetic capacity with Zn and B application.

By 60 DAS, parameters showed marked improvement. Plant height ranged from 215.50 cm (T<sub>5</sub>: RDF + Borax 2 kg ha<sup>-1</sup> B) to 238.83 cm (T<sub>9</sub>: RDF + ZnSO<sub>4</sub> 10 kg ha<sup>-1</sup> Zn + Borax 2 kg ha<sup>-1</sup> B), emphasizing the positive role of

combined micronutrient supply in promoting vegetative growth. The number of leaves per plant ranged from 11.27 (T<sub>4</sub>) to 14.22 (T<sub>3</sub>), while stem diameter increased up to 27.94 mm, with the greatest thickness recorded in T<sub>8</sub>. Dry matter accumulation at 60 DAS also showed significant increases (85.87 g to 118.43 g), particularly in T<sub>6</sub>, indicating strong biomass production influenced by Zn fertilization.

Chlorophyll content increased correspondingly (1.89–2.65 mg g<sup>-1</sup>), with the highest values in T<sub>12</sub>, followed by T<sub>9</sub> and T<sub>8</sub>. Such enhancements in chlorophyll content are known to correlate with improved photosynthetic performance and nutrient use efficiency under combined micronutrient applications.

### Influence of Zn and B application on Maize Yield and Yield Attributes

The pooled data clearly indicate that the applied treatments exerted significant effects on grain yield and cob morphological attributes in maize. Treatments T<sub>8</sub> RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn) + Borax (1 kg ha<sup>-1</sup> B), T<sub>5</sub> RDF+ Borax (2 kg ha<sup>-1</sup>, B), T<sub>7</sub> RDF + ZnSO<sub>4</sub> (5 kg ha<sup>-1</sup> Zn) + Borax (2 kg ha<sup>-1</sup> B), T<sub>9</sub> RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn) + Borax (2 kg ha<sup>-1</sup> B), and T<sub>12</sub> RDF + foliar application of ZnSO<sub>4</sub> @ 0.5% + Borax @ 0.1% emerged as the most productive treatments in terms of grain yield. The superior yield performance under these treatments reflects the positive role of zinc and boron in reproductive development, assimilate translocation, and kernel formation in maize [4, 6]

Among the treatments, T<sub>8</sub> RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn) + Borax (1 kg ha<sup>-1</sup> B) recorded the highest grain yield while maintaining favourable cob traits, including moderate cob weight (374.23 g), diameter (66.03 mm), girth (57.72 mm), and length (38.67 cm). This indicates an optimal balance between sink sizes and assimilate supply, a key determinant of yield efficiency in maize [12]. Similar improvements in cob morphology under combined Zn and B

fertilization have been reported in recent field studies, where enhanced micronutrient availability improved pollen viability, kernel set, and cob development [4, 5]

High-yielding treatments such as T7, T9, and T10 also exhibited superior cob attributes, suggesting a strong positive relationship between grain yield and cob diameter, girth, and weight. These findings support recent reports that ear traits directly influence sink strength and kernel filling, thereby governing final grain yield in maize [3, 12] Zinc plays a crucial role in enzyme activation and carbohydrate metabolism, while boron facilitates sugar transport and cell wall integrity in reproductive tissues, collectively enhancing cob growth and kernel development [5, 6]

The notable performance of T10 (RDF + ZnSo<sub>4</sub> foliar @ 0.5%) in terms of cob weight (416.22 g), diameter (70.07 mm), and girth (62.40 mm), despite a comparatively lower grain yield (3.21 t/ha), suggests that foliar Zn application promoted strong individual cob development. However, the slightly reduced yield may be attributed to factors such as lower ear number per unit area or incomplete kernel filling, as observed in recent maize micronutrient studies under foliar fertilization regimes [4, 12]

In contrast, treatments such as T1 (RDF only), T4 RDF + Borax (1 kg ha<sup>-1</sup> B), and T6 RDF + ZnSO<sub>4</sub> (5 kg ha<sup>-1</sup> Zn) + Borax (1 kg ha<sup>-1</sup> B) consistently recorded lower grain yield and inferior cob characteristics. This indicates a sub-optimal micronutrient supply, reinforcing recent findings that inadequate or imbalanced Zn and B application limits reproductive efficiency and kernel development in maize [5, 13]

The statistically significant CD values across all yield and cob parameters confirm the reliability of treatment effects, while CV values below 13% reflect experimental precision. Overall, the results validate that optimized zinc and boron management—particularly through combined soil and foliar applications—significantly enhances maize productivity by improving cob morphology and grain yield. These findings are consistent with recent evidence emphasizing the role of integrated micronutrient management in achieving higher maize yields under field conditions [4, 6, 12]

## **Influence of Zn and B application on Maize quality parameters**

The results clearly demonstrate that grain quality attributes in maize, particularly starch, protein, and oil contents, were significantly influenced by nutrient management practices. The variation observed across treatments highlights the importance of balanced macro- and micronutrient supply in regulating biochemical processes associated with grain filling and quality formation.

Higher starch content recorded under treatments T9 (6.28%) RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup> Zn) + Borax (2 kg ha<sup>-1</sup> B), T8 and T6, compared with the lowest value 4.13% in T1 (RDF alone), may be attributed to enhanced nutrient-use efficiency and improved photosynthetic performance during the grain-filling period. Adequate nitrogen availability enhances chlorophyll synthesis and delays leaf senescence, thereby sustaining assimilate supply for prolonged starch accumulation in developing kernels [14]. Phosphorus further contributes by facilitating ATP production and energy transfer, which are essential for enzymatic reactions involved in starch biosynthesis and carbohydrate translocation [12]. The synergistic role of Zn and B in maintaining membrane stability and enzyme activation may have further improved carbohydrate metabolism and starch deposition in maize grains [6].

The significant improvement in grain quality attributes under combined zinc and boron treatments may be attributed to their synergistic roles in regulating physiological and biochemical processes during grain development. Zinc is essential for enzyme activation, protein synthesis, and chlorophyll formation, thereby enhancing photosynthetic efficiency and assimilate production, which ultimately supports greater starch deposition in developing kernels [15, 16]. Boron plays a critical role in carbohydrate translocation, cell wall formation, and reproductive development, facilitating efficient movement of sugars from source to sink and improving kernel filling [5, 17]. The enhanced protein content observed under Zn- and B-treated plots, ranging from approximately 4.5% to 6.3%, may be linked to improved nitrogen metabolism and enzyme activity involved in amino acid synthesis [4, 18]. Likewise, modest increases in oil content ranging from about 2.7% to 3.2% under inte-

grated micronutrient application could be associated with improved metabolic activity and enzymatic regulation during grain maturation [19, 12]. These findings confirm that balanced zinc and boron fertilization not only improves maize yield but also enhances grain nutritional quality in micronutrient-deficient red and lateritic soils.

The oil content was markedly higher in treatments T8 and T9, followed by T12 (RDF + foliar application of ZnSO<sub>4</sub> @ 0.5% + Borax @ 0.1%), suggesting the positive influence of integrated nutrient supply on lipid biosynthesis. Potassium plays a regulatory role in carbohydrate metabolism and activates enzymes associated with fatty acid synthesis, while sulphur is a structural component of essential amino acids and coenzymes involved in oil precursor formation [20]. Recent studies have confirmed that adequate potassium and sulphur nutrition enhances oil accumulation in cereal grains by improving fatty acid metabolism and energy availability during grain filling [12]. Furthermore, foliar application of Zn and B has been shown to improve nutrient remobilization efficiency and enzymatic activity, thereby supporting enhanced oil synthesis in maize kernels [4].

In contrast, lower protein and oil contents observed under T1 (RDF only) indicate insufficient micronutrient availability, which may have restricted enzymatic activity and nutrient assimilation required for quality compound synthesis. These findings reinforce recent evidence that imbalanced nutrient application limits grain nutritional quality despite acceptable yields [5, 14].

Overall, the observed variation in starch, protein, and oil contents across treatments confirms that balanced and integrated nutrient management, particularly involving zinc and boron, is critical not only for improving maize yield and cob development but also for enhancing grain nutritional quality. The results align with recent studies emphasizing the role of micronutrients in regulating biochemical pathways governing grain quality attributes in maize [4, 6].

## Conclusion

The results of the present study supported the fact that red and lateritic soils, which are inherently deficient in zinc and boron, responded well to balanced levels of micronutrient fertilizers. The soil application of Zn and B in combination resulted in significant improvement in vegetative growth, chlorophyll content, dry matter, grain yield, and grain quality parameters of maize over RDF application alone. Among all the treatments, RDF + ZnSO<sub>4</sub> (10 kg ha<sup>-1</sup>, Zn) + Borax (1 kg ha<sup>-1</sup>, B) (T<sub>8</sub>) performed better in improving grain yield and its quality parameters, while RDF + ZnSO<sub>4</sub> (5 kg ha<sup>-1</sup>, Zn) + Borax (1 kg ha<sup>-1</sup>, B) (T<sub>6</sub>) performed better in improving vegetative growth parameters. Though moderate effects were observed by using the foliar spray method, soil application of Zn and B together has been found to be more effective than the prevailing soil conditions. Balanced application of Zn and B along with NPK fertilizers can be recommended as a sustainable nutrient management technique for improving productivity and quality of maize crop in red and lateritic soils of West Bengal and other agroclimatic regions.

## Ethical Declaration

The authors declare that the present study was conducted in accordance with established ethical standards. No human participants or animals were involved in this research. The experimental work was carried out following institutional guidelines and good laboratory practices. All data presented in this manuscript are original, accurately recorded, and have not been fabricated, falsified, or selectively manipulated. The manuscript has not been published previously and is not under consideration for publication elsewhere. The authors also declare that there is no conflict of interest regarding the publication of this paper.

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