Effects of Iron and Boron Application Rates on Growth and Yield Parameters of Rice (*Oryza sativa* L. spp.)

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ABSTRACT

Iron (Fe) and boron (B) are essential micronutrients for rice growth, yet their optimal application rates for enhancing productivity in Sub-Saharan Africa remain poorly defined. This study evaluated the effects of varying levels of Fe and B fertilization on the growth and yield of rice (Oryza sativa L.). A pot experiment was conducted using two rice varieties, CRI-Agra and CRI-Enapa, arranged in a completely randomized block design with a 2 × 3 × 3 factorial structure (variety × Fe level × B level) and three replications. Treatments comprised three levels each of Fe and B applied singly and in combination, alongside a control without micronutrient application. Growth parameters, including germination percentage, plant height, chlorophyll content, and biomass accumulation, were assessed during crop development, while yield components and grain yield were measured at harvest.Application of Fe and B significantly improved growth and yield attributes relative to the control (p < 0.05). Significant treatment effects were observed for plant height, number of tillers, number of panicles, straw yield, harvest index, and 100-seed weight. Combined application of Fe and B produced superior responses compared with sole applications, indicating a synergistic effect. Treatments $Fe_{12}B_{0.45}$, $Fe_{18}B_{0.3}$, and $Fe_{18}B_{0.45}$ consistently resulted in enhanced vegetative growth and yield performance across both varieties. Grain yield increased by up to 25% in selected treatments compared with the control. Improved chlorophyll content and biomass accumulation under Fe and B application suggest enhanced photosynthetic efficiency. Post-harvest soil analysis indicated increased micronutrient availability in treated pots.The findings demonstrate that appropriate Fe and B fertilization can significantly enhance rice growth and yield under controlled conditions. These results highlight the importance of optimizing micronutrient management for rice production; however, field-based validation across diverse agro-ecological conditions is required before broad agronomic recommendations can be made.

Keywords: Rice (Oryza sativa L.), iron fertilization; boron fertilization; micronutrients; growth parameters; yield components; pot experiment;Sub-Saharan Africa.

1. Introduction

Over half of the world's population is fed by rice, making it one of the most important staple crops in the world. As a vital food source and cash crop, rice holds a prominent position in the Ghanaian economy as a strategic crop [1]. The importance of rice to the Ghanaian economy, which makes up 15% of GDP, cannot be overstated [2]. Rice farming has become increasingly important in response to the fast-paced urbanization, population growth, and shifts in consumer preferences. Being the second most common cereal staple after maize, it significantly improves family food security in Ghana and Africa [3].

Fertilizer application rates by smallholder farmers in Sub-Saharan Africa (SSA) remain substantially behind those of other developing countries, despite the fact that fertilizer use increases agricultural production in the region and has been employed as a coping mechanism to control soil erosion. [4] claim that the average fertilizer application rate in Sub-Saharan Africa (SSA) is low, with estimates of as little as 16 kg/ha [5]. In comparison, the [6] World Bank (2014) reports that this rate is 90 kg/ha in the Middle East and North Africa, 126.6 kg/ha in North America, 127.9 kg/ha in Latin America and the Caribbean, 158.5 kg/ha in South Asia, and 344.3 kg/ha in East Asia and the Pacific region. The 2007–2008 worldwide food insecurity crisis was a big concern for people everywhere. Various governments responded to this circumstance in different ways. The creation and execution of the fertilizer subsidy policy in 2008 to boost domestic agricultural production was one of Ghana's attempts to fight this situation [7]. The objective was to boost agricultural output by encouraging farmers to apply more fertilizer, particularly to crops that are important for food security, like rice, maize, soybeans, and cowpeas.

Micronutrient deficiencies are believed to be one of the primary reasons behind the declining productivity trends in rice-growing nations such as Ghana. Micronutrient deficiencies are as vital to plant nutrition as macronutrient deficiencies. Although micronutrients are only slightly necessary, having an adequate supply increases nutrient availability and has a positive impact on cell physiology, both of which are reflected in yield [8]. Farmers often apply large amounts of N, P, K, and S fertilizers; however, they rarely add micronutrients like Fe, Zn, Cu, Mn, and B [9]. Because of heavy cropping, the loss of rich topsoil, and leaching, there is an alarming global prevalence of micronutrient-deficient soils [10]. Crop development and yield are significantly reduced when micronutrient levels are low [11]. The plants are unable to receive the full benefits of NPK fertilizer application when micronutrient deficiencies exist [12]. The quantity and quality of food produced aredrastically reduced due to micronutrient deficiencies in 50% of the world's soils and many crops, which has a negative impact on global environmental conditions, farmer livelihoods, and public health [13].

Micronutrients such as iron (Fe) and boron (B) are essential for optimal rice growth and productivity [14]. Deficiencies in these elements, especially in tropical and subtropical regions with inherently low micronutrient availability or high soil pH, often result in poor plant health and reduced yields [15]. The use of flora (liquid or foliar-based) fertilizers containing Fe and B has been explored to correct such deficiencies and improve plant physiological and reproductive functions [16]. Even while these nutrients actively participate in a number of plant growth processes, more research is still needed to determine how specifically they can increase crop output. More research is required to determine the precise effects of administering micronutrients in conjunction with NPK to rice crops in soils poor in micronutrients and under certain climate conditions. Crop productivity can only be increased by identifying the limiting micronutrient (s) and adding those nutrients to a well-balanced fertilizer program to enrich the soil. The objectives of this study were to investigate the effects of three levels of boron, iron and their combination on the variety of grain and straw yield of two rice varieties and the growth and yield of these varieties.

2. Materials and Methods
2.1 Material and location
Two rice varieties, CRI-Agra and CRI-Enapa, were obtained from the Rice Breeding Unit of the CSIR–Crops Research Institute (latitude 6°43′4.26″ N; longitude 1°31′54.13″ W) for use in this study. The experiment was conducted as a pot trial at the Rice Breeding Nursery, Fumesua–Kumasi.

The study was laid out in a randomized complete block design with a factorial arrangement consisting of two varieties × three iron (Fe) concentration levels (0%, 12%, and 18%) × three boron (B) concentration levels (0%, 30%, and 45%), with three replications (Figure 1 and Figure 2).Soil samples were analyzed for various physicochemical properties, and plant growth and yield attributes were measured at multiple growth stages (Table 1).

Figuree 1: Single micronutrient (Iron)

Figure 2: Single micronutrient (Boron)

Table 1: Initial Soil Physico-Chemical Properties Before Planting

Parameter	Method Used	Value	Unit
Soil pH (1:2.5 H_2O)	Jackson (1973) [17]	5.8	–
Electrical Conductivity	Black, C.A. (1965) [18]	0.15	dS/m
Organic Carbon	Walkley (1934) [19]	1.25	%
Available Nitrogen	Subbiah&Asija (1956) [20]	120	mg/kg
Available Phosphorus	Olsen et al. (1954) [21]	15.2	mg/kg
Available Potassium	Hanway&Heidel (1952) [22]	140	mg/kg
Available Sulphur	Williams &Steinbergs (1969) [23]	10.5	mg/kg
Available Boron	Berger &Troug (1993) [24]	0.45	mg/kg

2.2 Soil Analysis
Soil samples were collected from the soil used for the pot experiment. Depth from each plot. These samples were processed and analyzed for various physico-chemical properties in the laboratory of the Department of plant and soil Chemistry laboratory, in CSIR-Soil Research Institute. Soil pH (1:2.5 soil water) was determined by pH meter [17]. EC (dS m-1 at 25oC) (1:2.5 Soil: Water) was determined EC meter [18]. Organic carbon (%) was determined by [19] method. Available nitrogen in soil was determined by alkaline potassium permanganate method [20]. Available phosphorus was determined by Ascorbic acid method [21]. Available K in the soil was determined by the extraction method [22]. Available sulphur was determined by the turbid metric procedure[23]. and available boron in soil was determined by hot water extraction method of soil as developed by [24].

2.2. Data collection
2.2.1 Plant growth and yield attributes
Growth and yield data were collected using standard agronomic procedures. In each plot, four representative plants were randomly selected and tagged for repeated measurements throughout the growing period.

***2.2.1.1.** Plant height* was measured at 4, 6, 8, and 10 weeks after planting (WAP) using a measuring ruler. Measurements were taken from the soil surface to the tip of the fully expanded uppermost leaf, and the mean plant height per plot was calculated.

2.2.1.2.The number of tillers per plant* was recorded from the tagged plants at 4, 6, 8, and 10 WAP. At physiological maturity, the number of panicles per plant was counted from the same tagged plants.

***2.2.1.3.** Days to 50% flowering* were determined as the number of days from planting until approximately half of the plants in each plot had initiated flowering.

***2.2.1.4.** Leaf chlorophyll content* was assessed at 4, 6, 8, and 10 WAP using a CCM-200 Plus chlorophyll content meter, following the manufacturer's guidelines.

2.2.1.5. *The maturity period* was recorded as the number of days from planting to physiological maturity.

2.2.1.6. At harvest, plants from each plot were harvested separately, bundled, and weighed to obtain biological yield. Threshing was carried out manually one week after harvest to separate grain from straw. *1000 seed weight in grams* was recorded after threshing, while straw yield was determined by subtracting grain yield from biological yield. *The harvest index* was calculated as the ratio of grain yield to biological yield.

2.4 Data Analysis

The data were analyzed using Statistical Tool for Agricultural Research version 6, with means separation using Tukey's Honest Significant Difference (HSD) test for response variables at a 5% significance level.

Figure 3: Rice growth Control

Figure 4: Rice yield control

Figure 5: Rice growth after application of micro nutrient

Figure 6: Rice yield after application of micro nutrient

4.Results

Iron plays a critical role in chlorophyll synthesis, electron transport in photosynthesis, and enzymatic functions [25]. Boron, on the other hand, is vital for cell wall development, reproductive growth, and translocation of sugars [26]. In rice, Fe deficiency typically manifests as interveinal chlorosis in younger leaves, while B deficiency leads to sterility, poor panicle formation, and incomplete grain filling.

4.1 Plant Height Response to Iron and Boron Fertilizer Application

The application of different levels of iron (Fe) and boron (B) significantly influenced plant height at 4 weeks after planting (WAP), while no statistically significant differences were observed at 6, 8, and 10 WAP (Table 2). This indicates that the effect of micronutrient treatments on early vegetative growth was more pronounced than during the later stages of development, possibly due to early uptake and utilization efficiency. At 4 WAP, both varieties, Agra Rice and Enapa, responded differently to the Fe-B treatments.

The highest plant height in Enapa (43.03 cm) was recorded under the $Fe_{12}B_{0.3}$ treatments, while the lowest (38.42 cm) was observed under $Fe_{18}B_0$. In Agra Rice, differences were not statistically significant across treatments (42.62–44.47 cm), as indicated by the shared letter groupings in the table. By 10 WAP, Enapa exhibited the tallest plants under $Fe_{12}B_{0.3}$ (84.23 cm), indicating a strong positive response to this balanced micronutrient treatment. The lowest plant height (75.43 cm) in Enapa was recorded under $Fe_0B_{0.3}$, suggesting that iron played a critical role in the later stages of growth. Similarly, Agra Rice recorded its highest plant height (79.35 cm) under $Fe_{18}B_0$ and the lowest (72.78 cm) under Fe_0B_0, highlighting the contribution of iron in enhancing plant height even in the absence of boron. The response of the two rice varieties, CRI-Agra and CRI-Enapa, to different levels of iron (Fe) and boron (B) over 4, 6, 8, and 10 weeks after planting is presented in Table 2.

Plant Height at 4 Weeks: CRI-Agra consistently exhibited taller seedlings across most treatments, with heights ranging from 41.10 cm ($Fe_{12}B_{0.3}$) to 44.72 cm ($Fe_{12}B_{0.45}$). CRI-Enapa showed lower early growth in most treatments, with the exception of treatments containing 0.3% B ($Fe_0B_{0.3}$ and $Fe_{12}B_{0.3}$), where heights were comparable to CRI-Agra (42.18 cm and 43.03 cm, respectively). The HSD value of 4.64 indicates that significant differences at 4 weeks occurred primarily between treatments with contrasting B levels within the same Fe concentration.

Plant Height at 6 Weeks: Plant height increased in both varieties over time. CRI-Agra reached 67.87 cm in the $Fe_{18}B_{0.45}$ treatments, while CRI-Enapa attained 65.65 cm under $Fe_{12}B_{0.3}$. Overall, Fe and B application enhanced growth, though responses varied by variety. CRI-Agra showed slightly higher growth under higher Fe levels (12% and 18%), whereas Enapa's response was more influenced by combined B application.

Plant Height at 8 Weeks: By 8 weeks, CRI-Agra heights ranged from 66.43 cm to 71.02 cm, while CRI-Enapa ranged from 63.67 cm to 71.67 cm. The highest Enapa height was observed at $Fe_{12}B_{0.3}$ (71.67 cm), indicating that moderate B combined with Fe improved elongation. CRI-Agra maintained relatively uniform growth across treatments, suggesting a more stable response to micronutrient application.

Plant Height at 10 Weeks: At 10 weeks, CRI-Enapa surpassed CRI-Agra in most treatments, reaching a maximum height of 84.23 cm under $Fe_{12}B_{0.3}$. CRI-Agra reached a maximum of 79.35 cm ($Fe_{18}B_0$). This indicates that although CRI-Agra started taller, Enapa exhibited faster late-stage elongation, particularly under moderate B application.

In conclusion, CRI-Agra exhibited stronger early growth, while Enapa showed more pronounced late-stage elongation under certain Fe-B combinations. On Iron effects, higher Fe levels (12–18%) generally improved plant height in both varieties, especially when combined with B at 0.3–0.45%.Moderate B application (0.3%) positively influenced height, particularly for CRI-Enapa at later stages.The combination of Fe12B0.3 produced the tallest plants for CRI-Enapa, suggesting synergistic effects of Fe and B on late vegetative growth.

The coefficient of variation (CV%) ranged from 4.61% to 11.80%, indicating moderate variability in plant height measurements across treatments. Standard deviations were generally higher in Enapa, reflecting a more variable response to nutrient application

Table 2: Plant height(cm) response to different levels of iron, boron and their combination

Treatments	Plant Height 4wk		Plant Height 6wk		Plant Height 8wk		Plant Height 10wk	
	V(AgraRice)	V(Enapa)	V(AgraRice)	V(Enapa)	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)
Fe_0B_0	44.47 a	38.68 b	64.68	56.9	69.97	64	72.78	77.8
$Fe_0B_{0.3}$	42.62 a	42.18 a	61.73	59.78	67.18	68.6	75.93	75.43
$Fe_0B_{0.45}$	43.05 a	38.73 b	60.93	57.5	68.52	64.43	77.63	79.58
$Fe_{12}B_0$	44.25 a	39.15 b	62.58	61.02	70.33	64.85	76.37	79.18
$Fe_{12}B_{0.3}$	41.10 a	43.03 a	62.33	65.65	66.43	71.67	73.98	84.23
$Fe_{12}B_{0.45}$	42.72 a	39.47 b	65.63	61.8	70.05	64.15	76.12	81.05
$Fe_{18}B_0$	41.33 a	38.42 b	66.53	58.45	69.92	63.67	79.35	78.3
$Fe_{18}B_{0.3}$	43.62 a	39.40 b	67.68	62.18	70.93	68.63	75.62	81.63
$Fe_{18}B_{0.45}$	42.32 a	39.80 a	67.87	62.62	71.02	67.3	77.82	82.15
CV(%)	4.61	6.19	11.8	7.72	8.24	8.51	8.71	10.14
Mean	42.83	39.87	64.44	60.66	69.37	66.37	76.18	79.93
StdDev	2.13	2.75	7.44	5.07	5.49	5.85	6.4	7.88
HSD (0.05)		4.64						

Means with the same letter are not significantly different

4.2 Number of Tillers Response to Iron and Boron Application

Iron and boron treatments significantly influenced the number of tillers per plant across growth stages in both rice varieties (CRI-Agra and CRI-Enapa), with clear treatment separation evident from 6 weeks after planting (WAP) onward.

At 4 WAP, tiller numbers were generally low, ranging from 3 to 5 across treatments. The control (Fe_0B_0) consistently produced the lowest number of tillers in both varieties (3 tillers), while most Fe–B combinations recorded 4–5 tillers. Differences at this stage were modest but statistically significant, indicating early responsiveness to micronutrient application.

By 6 WAP, treatment effects became more pronounced. The control recorded the lowest tiller numbers (6 tillers in both varieties). Higher tiller production was observed under combined Fe and B applications, particularly $Fe_0B_0.3$, $Fe_0B_0.45$, and $Fe_{18}B_0.3$, which produced 15–17 tillers and were statistically superior to most other treatments. CRI-AgraR generally showed slightly lower tiller counts than Enapa, though the ranking of treatments was similar.

At 8 WAP, combined Fe and B treatments maintained their superiority. The highest tiller numbers (17–19 tillers) were recorded under $Fe_0B_0.3$, $Fe_0B_0.45$, $Fe_{12}B_0$, and $Fe_{18}B_0.3$ in both varieties. The control and Fe-only treatments without B (Fe_0B_0 and $Fe_{18}B_0$) consistently produced significantly fewer tillers (11–12 tillers), confirming the importance of boron in sustaining vegetative proliferation.

At 10 WAP, tiller numbers peaked across treatments. $Fe_0B_0.3$ and $Fe_{18}B_0.3$ recorded the highest tiller counts, reaching 22 tillers in CRI-Agra and up to 25 tillers in Enapa, and were significantly higher than most other treatments. The control remained the poorest performer (7 tillers in both varieties). Overall, Enapa tended to produce slightly higher tiller numbers than CRI-Agra at this stage, particularly under higher Fe–B combinations.

Across all sampling periods, combined Fe and B applications outperformed the control and single-nutrient treatments, with $Fe_0B_0.3$, $Fe_0B_0.45$, and $Fe_{18}B_0.3$ emerging as the most consistent treatments for enhancing tiller production.

Coefficients of variation ranged from 12.35% to 16.62%, indicating acceptable experimental precision, while mean tiller numbers increased steadily with crop age, confirming normal crop development and a strong treatment response.

4.3 Panicle number, straw yield, harvest index, and 100-seed weight as affected by iron and boron application

Iron and boron treatments significantly affected panicle production, straw yield, harvest index, and 100-seed weight in both rice varieties (CRI-Agra and CRI-Enapa), with clear differences among treatments.

The number of panicles per plant was lowest under the control (Fe_0B_0), which produced 7 panicles in both varieties. All Fe–B combinations significantly increased panicle number, with most treatments recording 11–14 panicles. In CRI-AgraR, $Fe_0B_0.3$, $Fe_0B_0.45$, $Fe_{12}B_0$, $Fe_{18}B_0$, and $Fe_{18}B_0.45$ produced the highest panicle numbers (13–14), while in Enapa similar trends were observed, although $Fe_{12}B_0.45$ recorded a slightly lower value (11 panicles). Overall, micronutrient application nearly doubled panicle number compared with the control.

Straw yield responded strongly to Fe and B application, particularly in CRI-Agra. The control recorded relatively low straw yields (541.05 and 479.19 kg ha^{-1} for CRI-Agra and Enapa, respectively). The highest straw yield in CRI-Agra was obtained under $Fe_{18}B_0$ (748.27 kg ha^{-1}), followed closely by $Fe_{18}B_0._3$ and $Fe_{18}B_0.45$, which were statistically similar. In Enapa, maximum straw yield was recorded under $Fe_{12}B_0._{45}$ (611.90 kg ha^{-1}), followed by $Fe_{12}B_0._3$ and $Fe_{18}B_0$. Treatments without boron generally produced lower straw yields than those with combined Fe and B.

4.5 Harvest Index Response to Iron and Boron Application

The harvest index (HI) was significantly improved by micronutrient application relative to the control. The lowest HI was recorded under Fe_0B_0 (0.27 in CRI-Agra and 0.42 in CRI-Enapa). Most Fe–B combinations resulted in higher HI values (0.41–0.51), with $Fe_{12}B_0.3$ producing the highest HI in CRI-Agra (0.51) and $Fe_{18}B_0.45$ and $Fe_{18}B_0$ producing the highest values in Enapa (0.51 and 0.49, respectively) (Table 4).

These results indicate improved partitioning of biomass to grain under combined Fe and B nutrition.

4.6 100 seed weight (g) Response to Iron and Boron Application

The 100-seed weight was also influenced by treatment, though varietal responses differed. In AgraR, the highest 100-seed weight was recorded under $Fe_{18}B_0$ (3.36 g), which was significantly higher than all other treatments. In Enapa, 100-seed weight varied within a narrower range (2.47–2.70 g), with $Fe_{12}B_0.45$ producing the highest value (2.70 g). The control recorded comparatively lower seed weights in both varieties.

Overall, coefficients of variation were low to moderate (4.53–17.93%), indicating acceptable experimental precision. The results demonstrate that combined iron and boron application substantially enhanced panicle number, straw yield, harvest index, and seed weight compared with the control, with higher Fe levels (12–18) combined with boron (0.3–0.45) generally producing the most favorable responses in both rice varieties. As shown in Table 4.

Table 3: Number of tillers (NoT) response to different levels of iron, boron and their combination

Treatment	NoT4wk		NoT6wk		NoT8wk		NoT10wk	
	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)
Fe_0B_0	3 c	3 b	6 e	6 d	6 c	6 c	7 d	7d
$Fe_0B_{0.3}$	5 ab	5 ab	15 ab	16 a	17 a	18 a	22 a	20 ab
$Fe_0B_{0.45}$	5 ab	5 ab	15 ab	15 a	18 a	18 a	21 a	21 ab
$Fe_{12}B_0$	5 a	5 a	13 bc	14 ab	16 a	18 a	19 ab	20 ab
$Fe_{12}B_{0.3}$	4 ab	4 ab	11 cd	13 abc	12 b	17 a	15 bc	20 ab
$Fe_{12}B_{0.45}$	4 bc	5 a	10 d	16 a	11 b	18 a	13 c	19 b
$Fe_{18}B_0$	4 bc	4 ab	9 de	11 bc	11 b	12 b	13 c	14 c
$Fe_{18}B_{0.3}$	5 ab	5 a	15 ab	17 a	18 a	19 a	22 a	25 a
$Fe_{18}B_{0.45}$	5 ab	5 a	17 a	10 c	19 a	11 b	21 a	13 c
CV (%)	14.17	16.62	12.37	14.69	12.35	14.96	14.08	16.06
Mean	4.30	4.50	12.24	13.11	14.17	15.24	16.89	17.78
StdDev	0.82	0.86	3.74	3.80	4.48	4.62	5.60	17.78
HSD (0.05)	1.14	1.41	2.85	3.62	3.29	4.29	4.47	5.37

Means with the same letter are not significantly different.

Table 4: No of panicles, straw, harvest index and 100 seed weight to different levels of iron, boron and their combination

Treatment	No of Panicle		Straw yield kg/ha		Harvest Index		100 seed.wt/g	
	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)	V(AgraR)	V(Enapa)
Fe_0B_0	7 b	7 b	541.05 cd	479.19 abc	0.27 b	0.42 ab	2.57 bc	2.50 ab
$Fe_0B_{0.3}$	14 a	14 a	588.75 bc	468.80 bc	0.48 a	0.41 ab	2.88 a	2.64 ab
$Fe_0B_{0.45}$	13 a	14 a	487.70 d	427.33 c	0.43 a	0.37 ab	2.66 b	2.51 ab
$Fe_{12}B_0$	14 a	14 a	669.85 a	468.67 bc	0.44 a	0.42 ab	2.56 bc	2.47 b
$Fe_{12}B_{0.3}$	12 a	13 a	564.03 cd	593.82 ab	0.51 a	0.45 ab	2.64 b	2.62 ab
$Fe_{12}B_{0.45}$	13 a	11 ab	603.63 bc	611.90 a	0.47 a	0.34 b	2.63 b	2.70 a
$Fe_{18}B_0$	14 a	14 ab	748.27 a	584.53 ab	0.44 a	0.49 a	3.36 c	2.48 ab
$Fe_{18}B_{0.3}$	11 a	12 a	720.23 ab	528.48 abc	0.46 a	0.45 ab	2.55 bc	2.59 ab
$Fe_{18}B_{0.45}$	13 a	13 a	680.37 ab	547.18 abc	0.41 a	0.51 a	2.56 bc	2.58 ab
CV(%)	16.52	14.89	8.13	13.73	14.03	17.93	4.53	4.61
Mean	12	12	622.65	523.32	0.44	0.43	2.60	2.56
StdDev	2.76	3.29	95.10	90.90	0.09	0.09	0.17	0.13
HSD (0.05)	3.75	5.03	95.15	135.10	0.12	0.15	0.22	0.22

Means with the same letter are not significantly different.

5. Discussion

Agronomic practices involving fertilizer application have been proposed as a promising approach to enhance both productivity and grain quality in rice cultivation. However, the effectiveness of this management strategy depends on several variables, including the type of rice variety, soil fertility, and the method employed for fertilizer application [27]. In conductive environments, plant development relies not solely on photosynthesis, which limits grain size, but also on the compatibility between physiological sinks and sources, which influences grain weight. Improvement in yield attributes was probably due to proper utilization of all the available and terrestrial growth resources, which may be influenced by the good translocation of photosynthates to sink from the source, and finally expressed the maximum values of yield attributes under one seedling/hill [28], [29] and [30]. Crop fortified with Fe and B gave better results. It might be due to more growth and development of rice with better plant height and more periodic DMA and LAI. It also enhanced metabolic activity, which improved floral primordial development and the conversion of vegetative tillers into reproductive tillers. Boron plays a key role in the flowering and grain-setting processes in rice. Good seed setting, better pollination, reduced spike sterility, and increased grain formation were observed in various rice varieties due to boron nutrition [31]. A sufficient amount of iron in the soil provided different nutrient uptake, leading to enhanced plant growth and photosynthetic rates, thereby increasing the translocation of dry matter and ultimately boosting straw yield [32] and [33]. The increased economic yield could be attributed to a higher number of effective tillers/m2, enhanced dry matter accumulation, and other yield-contributing factors (Table), in addition to the translocation of photosynthates toward the sink [34], [35] and [36].

Plant height responses to iron (Fe) and boron (B) treatments in both rice varieties reflected developmental stage–specific nutrient effects and varietal differences. At early growth (4 WAP), treatment effects on height were minimal and statistically indistinct, which aligns with reports that micronutrient influence on height often manifests more clearly after initial establishment when vegetative growth intensifies (e.g., 30–60 DAS) rather than at very early stages when seed reserves dominate growth (Table 1; similar early insensitivity seen in micronutrient studies).Overall, plant height tended to increase under treatments where iron and boron were applied in balanced amounts. This is in agreement with findings by [37] and [38], who reported that the highest plant heights in rice were achieved under high and balanced micronutrient fertilization. The beneficial impact of micronutrients, particularly Fe and B, is likely linked to their roles in chlorophyll synthesis, energy transfer, and cell wall development, which are vital for vegetative growth and plant elongation.

From 6 WAP onward, combined Fe–B treatments tended to promote greater height compared with the control. This pattern is consistent with multiple studies indicating that adequate micronutrient availability enhances biological processes that underlie stem elongation. Iron is essential for chlorophyll synthesis and enzymatic systems involved in cell division and elongation, so improved Fe supply increases vegetative growth and plant height in cereals under non-deficient conditions (e.g., improved heights with Fe supplementation) [39]. Boron likewise plays a role in cell wall synthesis, membrane integrity, and carbohydrate transport, which supports sustained growth, though responses can vary with soil conditions and cultivar genetic background [40].These results suggest that $Fe_{12}B_{0.3}$ was the most effective treatment in promoting plant height in Enapa, while $Fe_{18}B_0$ was most effective for Agra Rice. Differences in varietal response also highlight the need to tailor micronutrient management strategies according to genotype and soil micronutrient status.

By 8–10 WAP, varietal differences became more evident. Enapa generally attained greater height under several Fe–B combinations (e.g., $Fe_{12}B_0$.3, $Fe_{18}B_0$.45), exceeding AgraR. This suggests a varietal variation in nutrient utilization efficiency; some genotypes can more effectively translate enhanced micronutrient supply into vegetative growth. Similar genotype–nutrient interactions have been reported in rice, where cultivar responses to Fe/B varied in magnitude and timing, particularly at later stages when vegetative and reproductive demands intensify. The increased grain yield resulting from iron nutrition primarily stemmed from enhanced crop growth, characterized by a greater number of productive tillers/m2, increased the filled grains per panicle, higher panicle weight, and 1,000-grain weight, along with an augmented supply of photosynthates from source to sink [41] and [42]. Higher nutrient content (%) in grains and straw was recorded under one seedling/hill as compared to two and three seedlings/hill. Intense competition among plants for growth factors, including nutrients, under higher plant density and the dilution effect could have led to lower nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and boron (B) content in sinks (Pradhan and Dixit, 2021). More nutrient content in grains and straw and their uptake were recorded due to the application of micronutrients iron and boron. As regards iron and boron nutrition, the highest ironand boron content in grain was recorded with foliar application of Fe and B nutrition during 2019 and 2020, respectively. Increased iron and boron concentrations in the grain could be attributed to greater transfer of these nutrients from the source to the sink (grain), particularly when higher doses of iron and boron were administered as foliar sprays during the later stages of growth [43] and [44]. Overall, the treatment $Fe_{18}B_{0.3}$ consistently produced the highest tiller counts in both varieties at the final growth stage. This suggests that a balanced supply of iron and boron enhances vegetative branching and tillering. The improved tiller production under these treatments may be attributed to increased metabolic activity, photosynthetic efficiency, and nutrient availability during critical vegetative phases.On the number of panicles, these findings align with earlier research [45], which reported that nitrogen and complementary micronutrients significantly enhanced vegetative growth attributes such as plant height and tiller number, ultimately contributing to higher straw yields.

These results on straw weight align with previous studies [46] and [47], which demonstrated that appropriate micronutrient application improves biomass production, possibly due to enhanced photosynthetic activity and nutrient use efficiency.Similar observations were reported by [48] and [49], who found on the harvest index that while boron may not directly affect vegetative parameters such as tiller number and plant height, it significantly contributes to reproductive efficiency and grain filling.

Adequate boron supply appears to be a prerequisite for obtaining optimum yields of good-quality basmati rice [50] and [36]. It is noteworthy to observe that in this investigation, the application of iron and boron led to an increase in the content of iron and boron in rice grain.

Although the accumulation of B and Fe in grains was enhanced, it did not impact the number of fertilized or filled grains during development [51]. Therefore, the foliar application of B during the panicle initiation stage could be a factor in enhancing rice crop productivity.

These results confirm that micronutrient applications, especially iron and boron, contribute to improved seed filling and grain quality. Findings are consistent with those of [52], [53], [54] and [55], who noted yield advantages under nutrient expert (NE)-guided practices. Supporting studies [56], [57], [58], [59], [60] and [61] also reported that rice grain yield and quality improved significantly due to the application of Fe and B either individually or in combination with other micronutrients. These improvements are likely due to the essential roles of Fe in chlorophyll synthesis and B in pollen viability and cell wall development.

Several studies have highlighted the positive effects of Fe fertilization on rice. For instance, [62] reported improved chlorophyll content and photosynthetic rate in rice with foliar Fe application, especially under flooded conditions where Fe availability is altered. [63] showed that applying $FeSO_4$ at 10–15 kg/ha increased tiller number, leaf area index, and ultimately grain yield by 12–18% compared to control treatments. Fe foliar sprays were found to be more effective than soil application in high-pH soils, where iron is often bound and unavailable to plants [64] and [65].

Research indicates that B is particularly important for reproductive development in rice. [66] found that B application at 2 kg/ha significantly increased spikelet fertility and panicle number. [67] observed that B improved pollen viability and grain setting, especially in clay loam soils deficient in B. Foliar application of B (as boric acid) during the reproductive stage was reported to increase grain yield by 10–20% in several trials in South Asia [68].

Limited but emerging research suggests synergistic effects when Fe and B are applied together, [69] demonstrated that foliar application of Fe (0.5%) and B (0.2%) at tillering and panicle initiation stages enhanced rice biomass, spikelet fertility, and yield by up to 25% over the control. A study by [70] on micronutrient interactions showed that balanced Fe and B nutrition mitigated micronutrient antagonism, enhanced nutrient use efficiency, and promoted better panicle development.

The efficiency of Fe and B fertilizers depends significantly on the mode and timing of application, Foliar applications are generally more efficient in correcting micronutrient deficiencies, especially in alkaline or calcareous soils [71]. Application during critical growth stages such as tillering and panicle initiation leads to higher responsiveness in rice [72]. Controlled-release flora fertilizers or micronutrient-enriched NPK blends (e.g., Fe-B-enriched urea) are being developed for sustained availability [73].In summary, the data show that combined Fe and B treatments improved rice plant height more consistently than the control or Fe alone, with growth differences increasing through mid to late vegetative stages, and with the Enapa variety showing a more pronounced height response under certain micronutrient regimes. This supports strategic application of Fe and B in rice production to maximize vegetative growth, though varietal choice will influence the magnitude of response.

6.Conclusions

Iron and boron are indispensable for healthy rice development and yield optimization. While individual applications improve growth and reproductive success, combined Fe-B flora fertilization offers synergistic benefits, particularly in micronutrient-deficient soils. However, rates, timing, and application methods must be tailored to specific soil and climatic conditions to maximize effectiveness.

The study demonstrated that the application of iron (Fe) and boron (B), individually or in combination, had significant positive effects on various growth and yield parameters of rice, including plant height, tiller number, panicle number, straw weight, harvest index, and 100-seed weight. Key findings include:

Plant Height and Tiller Number:Moderate to high levels of Fe and B application improved vegetative growth, contributing to increased plant height and tillering, especially in treatments involving Fe_{12} and Fe_{18} in combination with $B_{0.3}$ or $B_{0.45}$.

Panicle Number: Both varieties responded positively to Fe and B, with the highest panicle numbers (14) observed in several treatment combinations (e.g., $Fe_0B_{0.3}$, $Fe_{12}B_0$, $Fe_{18}B_0$), indicating enhanced reproductive development.

Straw Weight: Straw yield was significantly improved by Fe and B application. CRI-Agra showed the highest biomass under $Fe_{18}B_0$, while Enapa responded best under $Fe_{12}B_{0.45}$, suggesting varietal differences in nutrient use efficiency.

Harvest Index: Treatments such as $Fe_{12}B_{0.3}$ and $Fe_{18}B_{0.45}$ produced the highest harvest indices, demonstrating improved partitioning of assimilates towards grain production.

100-Seed Weight: Seed weight increased significantly with micronutrient application, with CRI-Agra reaching up to 3.36 g under $Fe_{18}B_0$, highlighting the positive impact of micronutrients on grain filling and quality.

Overall, the results indicate that integrated application of Fe and B enhances both vegetative and reproductive performance of rice, with treatment combinations such as $Fe_{12}B_{0.3}$, $Fe_{18}B_0$, and $Fe_{12}B_{0.45}$ consistently improving key agronomic traits.

7 Recommendations

Based on the findings, the following recommendations are proposed:

Adopt Micronutrient-Enriched Fertilization: Application of Fe and B should be integrated into rice nutrient management strategies, especially in micronutrient-deficient soils, to enhance productivity and grain quality.

Optimal Treatment Combinations:For CRI-Agra: $Fe_{18}B_0$ or $Fe_{12}B_{0.3}$ is recommended for maximizing grain yield and straw production. For Enapa: $Fe_{12}B_{0.45}$ showed consistent performance and may be adopted for improved yield and biomass.

Varietal Considerations: Responses to micronutrients vary between varieties; therefore, site-specific and variety-specific fertilizer recommendations should be developed.

Further Research: Multi-location field trials are recommended to validate these findings across different agro-ecological zones, and to refine application rates and timing for greater efficiency.

Capacity Building: Farmers should be trained on the importance of micronutrients in rice cultivation and on how to properly apply Fe and B through both soil and foliar methods.

Different treatments had varying effects on the studied rice varieties. Recommendations will be made accordingly to optimize nutrient management practices for improving rice yield and nutrient use efficiency in Sub-Saharan Africa.

Way forward

The recommended rates should be adopted for use at the research station to improve the growth and yield of rice in Ghana.

Abbreviations

SSA: sub-Saharan Africa
RNA: Ribonucleic Acid
HI: Harvest index
Mn: Manganese
Cu: Copper
Fe: Iron
B: Boron
Mo: Molybdenum
N: Nitrogen
P: Phosphorus
K: Potassium

Supplementary Material

There is or are no supplementary material

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Author Contributions

- **Charles Afriyie-Debrah:** Conceptualization, original draft, Investigation, Methodology
- **Maxwell Darko Asante:** Supervision and Funding acquisition
- **Kirpal Ofosu Agyemang:** Visualization
- **Elizabeth Norkor Nartey:** Validation
- **Daniel Gamenyah:** review & editing
- **Jacob Kporku, Kenneth Korfeator and Linda Bediako:** Data curation
- **Boampong Edward:** review & editing
- **Francisca Amoah Owusu:** review & editing

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