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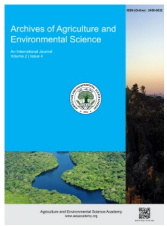

ORIGINAL RESEARCH ARTICLE

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Response of variety and sulphur on yield attributes and yield of *boro* rice in *Haor* area of Bangladesh

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ABSTRACT

The *haor* region of Bangladesh offers substantial scope to enhance *boro* rice productivity through improved soil nutrient management and adoption of high-yielding varieties. This study aimed to evaluate the interactive effects of rice variety and sulphur application on growth and yield performance under *haor* conditions. A field experiment was conducted at *Dhoronti Haor*, Nasirnagar, Brahmanbaria district of Bangladesh during January–April 2023 using four varieties—BRRI dhan28, BRRI dhan29, BRRI dhan89, and *Hira-2* (Hybrid)—and five sulphur levels (0, 55, 110, 165, and 220 kg S ha^{-1}) with recommended fertilizer doses. The experiment followed a split-plot design with three replications, assigning varieties to main plots and sulphur levels to subplots. Results revealed significant ($p < 0.05$) main and interaction effects of variety and sulphur on most growth and yield traits. The hybrid *Hira-2* produced the highest filled grains panicle^{-1} (323.0), panicle length (22.0 cm), thousand-grain weight (28.79 g), and grain yield (9.24 t ha^{-1}), whereas BRRI dhan28 showed the lowest performance. Sulphur application significantly improved yield attributes, with the optimum yield (7.42 t ha^{-1}) obtained at 165 kg S ha^{-1}, beyond which no further increase was observed. Variety × Sulphur interaction indicated that *Hira-2* and BRRI dhan89 were most responsive to moderate sulphur levels, while BRRI dhan28 showed limited response. The integration of hybrid rice variety *Hira-2* with an optimum sulphur rate of 165 kg S ha^{-1} can substantially enhance grain yield and resource-use efficiency, offering a sustainable intensification strategy for the *haor* agroecosystem.

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INTRODUCTION

Rice (*Oryza sativa* L.) is the principal staple food crop globally, serving as a key source of nourishment for over half of the world's population and playing a crucial role in ensuring food security across Asia (David, 1989; Islam *et al.*, 2024). In Bangladesh, rice accounts for nearly 90% of the country's total food grain output and serves as a cornerstone of the national economy (FAO, 2023). The country ranks third among the world's rice producers, with an annual output of 38.50 million metric tons from 11.70 million hectares (BBS, 2023). Of the three major rice-growing seasons—*Aus*, *Aman* and *Boro*—the *Boro* season contributes the largest share, accounting for nearly 58% of national production (BBS, 2023). This importance is particularly evident in ecologically distinctive areas such as the *haor* basin. *Haors* are large, saucer-shaped floodplains situated in the north-eastern districts of Bangladesh, including Sunamganj, Sylhet, Habiganj, Maulvibazar, Netrakona, Kishoreganj and Brahmanbaria (BHWD, 2012; Sultana *et al.*, 2022). Covering over 2.0 million hectares—approximately 14% of Bangladesh's total land area—these wetlands support a population of about 19.4 million (Bokhtiar *et al.*, 2024). Nearly 1.93 million hectares in the *haor*

area are under Boro rice cultivation, representing about 15–18% of the national rice area (BHWD, 2012). Due to prolonged monsoon inundation, *Boro* rice is effectively the only viable crop during the dry season (Huda, 2004). Farmers predominantly cultivate high-yielding varieties (HYVs) such as BRRI dhan28, BRRI dhan29 and BRRI dhan89, alongside limited hybrid and local cultivars (Aziz, 2016). In some upazilas, *boro* rice covers up to 92% of the cultivated land (BHWD, 2012). Despite its centrality, *boro* rice cultivation in *haor* areas faces severe agroecological challenges. Flash floods originating from upstream catchments in the Indian states of Assam and Meghalaya often occur between late March and early May, coinciding with the reproductive or maturity stages of *boro* rice (Islam *et al.*, 2024). Such floods can devastate up to 0.40 million hectares annually, causing economic losses estimated at Tk. 4,500 million—about 4% of national agricultural GDP (BHWD, 2012). For instance, in the 2016–17 season flash floods damaged 296,701 hectares across several districts (Salwa *et al.*, 2019). Periodic outbreaks of neck blast disease, such as those observed in Sunamganj in 2017–18, further undermine production (Salwa *et al.*, 2019).
Varietal selection is a critical strategy to mitigate these risks. Flash flooding threatens rice production, making early-maturing, submergence-tolerant varieties essential, with BRRI dhan74, BRRI dhan88, BRRI dhan100 (Bangabandhu dhan), and BRRI dhan81 outperforming BRRI dhan28 in yield and quality (Iftekharuddaula *et al.*, 2016; Roy *et al.*, 2022). Short-duration varieties such as BRRI dhan81 and BRRI dhan86 can be harvested 7–10 days earlier than long-duration varieties such as BRRI dhan29, potentially escaping late-season flooding (Saha, 2020). However, short-duration cultivars generally produce lower yields (Islam *et al.*, 2024), while long-duration varieties yield more but face greater flood risk (Akter *et al.*, 2025). This trade-off creates significant challenges for optimizing transplanting and harvesting schedules (Aziz, 2016). Research shows that BRRI dhan92 and BRRI dhan84 consistently outperform BRRI dhan28 in grain yield and yield-contributing traits under optimal management (Dey *et al.*, 2025; Islam *et al.*, 2025; Akter *et al.*, 2025). Nonetheless, early transplanting of short-duration varieties may induce cold stress at the reproductive stage, whereas delayed transplanting increases vulnerability to flash floods (Rashid & Yasmeen, 2018). Alongside varietal improvement, nutrient management—particularly sulphur (S) fertilization—is essential to maximize productivity. Sulphur is integral to amino acid and protein synthesis, enzymatic processes, and chlorophyll formation, accounting for about 90% of organic sulphur in plant tissues (Giri *et al.*, 2025). Sulphur deficiency in rice reduces tillering and ultimately grain yield (Blair & Lefroy, 1987). Although rice roots primarily absorb sulphur as sulphate, the crop is highly sensitive to even low concentrations of sulphide (Blair & Lefroy, 1987). Despite this, sulphur application in *haor* areas is often neglected, and fertilizer use remains imbalanced (Alam *et al.*, 2006), accelerating soil nutrient depletion and constraining yield potential. Research demonstrates that combining sulphur with nitrogen, phosphorus and potassium markedly improves grain yield and quality in high-yielding rice varieties (Bari *et al.*, 2023). For instance, in calcareous soils of AEZ-11, applying 20 kg S ha^{-1} with boron significantly enhanced tiller numbers, panicle length, grain weight and total yield compared to control plots (Bari *et al.*, 2023). Although previous studies have investigated varietal differences and nutrient management separately, few have examined their interaction under the unique hydro-ecological conditions of the *haor* region. Varietal differences in growth duration, tillering ability, and panicle size can interact with soil fertility management, influencing productivity. According to Salwa *et al.* (2019, 2020), the application of recommended fertilizer packages markedly enhanced the grain yield of BRRI dhan29 relative to the yields obtained under farmers' conventional practices. Gupta *et al.* (2023) found that hybrids and high-yielding inbred varieties clustered together based on principal component analysis, reflecting similar yield-contributing traits. Optimal sulphur fertilization may therefore differentially benefit varieties with contrasting growth durations and morphologies. Moreover, hybrids such as *Hira-5* and Arize 6444 Gold demonstrate higher yield potential than traditional inbred cultivars (Khanum *et al.*, 2023), but adoption remains limited due to seed cost and availability. Understanding whether sulphur fertilization can close the yield gap between inbred and hybrid cultivars is thus an important research priority.
Despite advances in rice breeding and fertilizer recommendations, significant knowledge gaps remain. Most studies assume uniform sulphur response across varieties, though uptake efficiency, phenology and biomass allocation differ among cultivars. The hydrology, soil fertility and stress patterns of the *haor* region also diverge from other rice-growing zones, necessitating site-specific recommendations. Furthermore, few studies have explicitly tested the interaction between variety and sulphur fertilization under *haor* conditions. Addressing these gaps is essential to promote resilient production systems capable of sustaining high yields while minimizing risk. Although considerable progress has been achieved in rice varietal development and fertilizer management, *boro* rice yields in the *haor* basin remain below their potential, primarily due to site-specific nutrient imbalances and limited understanding of varietal responses to sulphur nutrition. The interaction between genotype and sulphur under the unique hydro-ecological conditions of *haor* wetlands has not been comprehensively investigated. This knowledge gap constrains the development of site-specific fertilizer and varietal recommendations essential for optimizing productivity in this ecosystem. The present study is therefore distinctive in integrating varietal evaluation with graded sulphur fertilization to identify the most effective combination for sustainable yield enhancement. Addressing this issue is vital for improving nutrient-use efficiency, yield stability, and climate resilience in *boro* rice cultivation within the *haor* region. Therefore, this study was undertaken to address the critical research gap concerning the combined influence of varietal selection and sulphur nutrition under the unique hydro-ecological conditions of the *haor* basin, to develop site-specific nutrient and variety management strategies to enhance *boro* rice productivity and resilience. The objectives of this study were therefore to

evaluate the performance of different *boro* rice varieties with respect to yield attributes and grain yield; assess the effects of sulphur application on yield and yield-contributing characteristics; and to determine the interaction effects of variety and sulphur fertilization on the yield performance of *boro* rice.

MATERIALS AND METHODS

Study area

The field experiment was conducted at *Dhoronti Haor*, Nasirnagar Upazila, Brahmanbaria District (24.12° N, 91.10° E) during the *boro* season (January–April 2023) (Figure 1). The site is characterized by seasonal flooding, clay-loam soils, and a rice-dominated cropping system, typical of the north-eastern *haor* basin of Bangladesh (BHWD, 2012).

Experimental design and treatments

A split-plot design with three replications was used, with rice variety in the main plots and sulphur fertilization in subplots (Figure 2), following standard randomization procedures (Gomez & Gomez, 1984). Four different *boro* rice varieties will be evaluated: BRRI dhan28 (V_1), BRRI dhan29 (V_2), BRRI dhan89 (V_3), and Hybrid *Hira-2* (V_4). Five levels of sulphur fertilizer application will be tested, including T_0 (Control, no fertilizer applied), T_1 (Recommended dose of fertilizers: Urea, TSP, MOP, Gypsum, and $ZnSO_4$ @ 260 kg ha^{-1}, 100 kg ha^{-1}, 120 kg ha^{-1}, 110 kg ha^{-1}, and 11 kg ha^{-1}, respectively, as per FRG, 2022), T_2 (Recommended dose + Half of recommended sulphur dose, 55 kg S ha^{-1}), T_3 (Recommended dose + One and half times the recommended sulphur dose, 165 kg S ha^{-1}), and T_4 (Recommended dose + Double the recommended sulphur dose, 220 kg S ha^{-1}). Seedlings aged 25 days were transplanted at a spacing of 25 cm × 15 cm, maintaining three seedlings per hill. Uniform management practices such as irrigation, weed control, and pest management were consistently implemented throughout the experiment (BRRI, 2018).

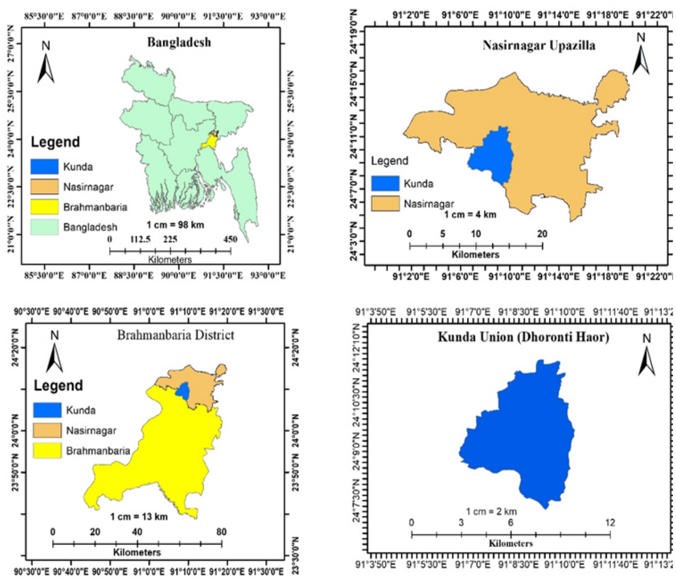

Figure 1. *The map showing experimental location of dhoronti haor (Wetland) of Bangladesh.*

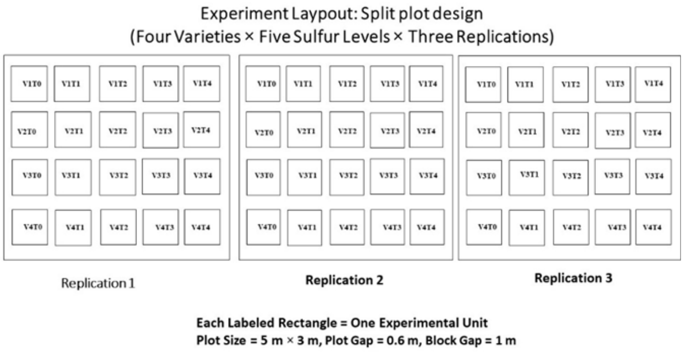

Figure 2. *Experimental layout of the split-plot design (Four varieties × five sulphur levels × three replications).*

Data collection

Growth and yield-contributing traits were recorded following standard procedures (Yoshida *et al.*, 1976): plant height, total and effective tillers per hill, panicle length, filled and unfilled grains per panicle, and thousand-grain weight. Yield parameters measured included grain yield, straw yield, biological yield, and harvest index.

Statistical analysis

Data analysis was conducted using R software (version 4.5.1). Analysis of variance (ANOVA) followed the procedure described by Gomez and Gomez (1984), and treatment means were separated using the least significant difference (LSD) test at the 5% significance level to determine statistical differences among treatments.

RESULTS AND DISCUSSION

Growth attributes of *boro* rice as influenced by variety, sulphur, and their interaction

Rice varieties showed significant differences ($p < 0.05$) in plant height, total tiller number, effective tillers, and non-effective tillers per hill (Table 1). Among the tested varieties, BRRI dhan89 produced the tallest plants (106.73 cm), followed by Hybrid *Hira-2* (100.23 cm) and BRRI dhan28 (91.19 cm), whereas BRRI dhan29 produced the shortest plants (79.21 cm). The superior height of BRRI dhan89 may be attributed to its longer growth duration, greater biomass accumulation, and higher nutrient uptake efficiency (Dey *et al.*, 2025; Akter *et al.*, 2025). These findings align with previous studies showing that long-duration varieties, such as BRRI dhan92 and BRRI dhan89, generally achieve greater plant height compared to short-duration varieties under *haor* conditions (Dey *et al.*, 2025; Islam *et al.*, 2025). Hybrid rice varieties, including *Hira-2*, also displayed enhanced vegetative growth, likely due to heterosis effects that promote higher cell division rates and leaf area expansion, supporting more vigorous growth (Wang *et al.*, 2024). Total tillers hill^{-1} were highest in BRRI dhan89 (25.13), followed by BRRI dhan28 (19.33) and BRRI dhan29 (16.00). Similarly, effective tillers hill^{-1} were significantly greater in BRRI dhan89, while non-effective tillers were highest in BRRI dhan29. The superior tillering of BRRI dhan89 may result from enhanced meristematic ac-

Table 1. Effect of variety on growth and yield attributes of *boro* rice in the *Haor* region of Bangladesh.

Variety (V)	Plant Height at Harvest	Number of total tillers hill^{-1}	Number of effective tiller hill^{-1}	Number of non-effective tiller hill^{-1}	Number of filled grain per panicle	Number of unfilled grain panicle	Panicle length (cm)	Thousand-grain weight (g)
V_1	91.19±4.86c	19.33±2.49b	19.13±2.64b	0.20±0.42ab	91.53±2.50d	19.33±3.58a	18.27±3.63c	21.77±0.39d
V_2	79.214±3.82d	16.00±1.96c	15.67±2.22c	0.33±0.48a	190.60±6.32c	14.40±3.44b	21.67±1.67ab	25.04±0.49b
V_3	106.73±5.46a	25.13±2.53a	25.13±2.53a	0.00±0.00b	170.33±7.52b	4.20±1.21c	22.67±1.58a	24.46±0.59c
V_4	100.23±3.74b	9.73±1.75d	9.73±1.75d	0.00±0.00b	323.00±13.41a	0.20±0.40d	20.73±1.58b	28.79±0.57a
CV	4.36	8.38	9.03	259.04	3.39	27.83	7.42	2.12
Level of sig.	***	***	***	*	***	***	***	***

Values are presented as mean ± standard error (SE). Means within a column followed by different letters (a–d) differ significantly at the 5% level of probability according to Duncan's Multiple Range Test (DMRT). CV = Coefficient of Variation. Level of significance: ns = non-significant, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. V_1= BRRI dhan 28, V_2= BRRI dhan 29, V_3= BRRI dhan 89 and V_4= *Hira-2* (Hybrid).

Table 2. Effect of sulphur levels on growth and yield attributes of *boro* rice in the *Haor* region of Bangladesh.

Sulphur (T)	Plant Height at Harvest	Number of total tillers hill^{-1}	Number of effective tiller hill^{-1}	Number of non-effective tiller hill^{-1}	Number of filled grain per panicle	Number of unfilled grain panicle	Panicle length (cm)	Thousand-grain weight (g)
T_0	90.73±10.65b	14.75±5.75c	14.50±5.85c	0.25±0.45	164.4±89.2c	11.0±9.37	18.33±3.70b	25.0±2.57ab
T_1	92.52±11.79a	18.83±6.45a	18.83±6.45a	0.00±0.00	179.8±99.5a	9.08±8.11	21.67±2.10a	25.13±2.63ab
T_2	93.04±11.26a	18.50±6.76ab	18.33±6.77ab	0.17±0.39	176.6±96.6ab	10.08±9.19	21.00±2.08a	24.81±2.64b
T_3	95.35±12.52ab	17.50±5.35b	17.42±5.40b	0.08±0.28	174.5±92.9b	8.83±7.92	22.00±1.85a	25.31±2.88a
T_4	96.06±11.18a	18.17±5.78ab	18.00±5.78ab	0.17±0.39	172.6±98.0b	8.92±7.43	21.17±2.48a	24.84±2.58ab
CV	4.36	8.38	9.03	259.04	3.39	27.83	7.42	2.12
Level of Sig.	**	***	***	ns	***	ns	***	*

Values are presented as mean ± standard error (SE). Means within a column followed by different letters (a–c) differ significantly at the 5% level of probability according to Duncan's Multiple Range Test (DMRT). CV = Coefficient of Variation, Level of significance: ns = non-significant, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.T_0=No fertilizer, T_1= Recommended rate of fertilizer Urea, TSP, MOP, Gypsum, and $ZnSO_4$ @ 260 Kg ha^{-1}, 100 Kg ha^{-1}, 120 Kg ha^{-1}, 110 Kg ha^{-1}, and 11 Kg ha^{-1}, T_2= Recommended rate + Half of recommended dose sulphur fertilizer (55 Kg ha^{-1}), T_3= Recommended rate + One and half of recommended dose sulphur fertilizer (165 Kg ha^{-1}), and T_4= Recommended rate + Double of recommended dose sulphur fertilizer (220 Kg ha^{-1}).

tivity, improved nutrient use efficiency, and longer vegetative phase (Bari *et al.*, 2023; Akter *et al.*, 2025). Conversely, BRRI dhan29 produced more non-productive tillers, possibly due to genetic limitations in assimilate partitioning under *haor*-specific conditions, consistent with Salwa *et al.* (2020) and Dey *et al.* (2025). Although sulphur fertilization did not significantly affect growth traits (Table 2), a clear positive trend was observed up to the double dose (T_4). The tallest plants (96.06 cm) and maximum tillers hill^{-1} (18.17) were recorded under T_4, suggesting that sulphur supports vegetative growth by enhancing chlorophyll synthesis, amino acid production, and overall metabolic activity (Rahman *et al.*, 2016; Bari *et al.*, 2023). However, excessive sulphur beyond optimal levels may reduce tiller formation due to nutrient imbalance, highlighting the need to match sulphur application with varietal nutrient requirements (Akter *et al.*, 2025). The combined effect of variety and sulphur level was statistically significant for plant height, total tillers, and effective tillers per hill (Table 3). The tallest plants (108.4 cm) were observed in BRRI dhan89 at the double sulphur dose (220 kg S ha^{-1}), whereas the shortest (76.39 cm) occurred in BRRI dhan29 at half the recommended dose (55 kg S ha^{-1}). Interestingly, the highest total and effective tillers (28 hill^{-1}) were recorded in BRRI dhan29 at the recommended sulphur dose (110 kg S ha^{-1}). This indicates that varietal differences in nutrient use efficiency strongly influence growth responses, emphasizing the importance of integrated nutrient and varietal management (Akter *et al.*, 2025; Islam *et al.*, 2025). The observed growth patterns are consistent with recent findings. For instance, Salwa *et al.* (2020) reported that BRRI dhan28 and BRRI dhan29 exhibited high tillering under optimal fertility, whereas Dey *et al.* (2025) highlighted that long-duration varieties like BRRI dhan89 and BRRI dhan92 achieve greater plant height and tiller numbers in *haor* ecosystems. Similarly, hybrid varieties consistently outperformed inbred lines in vegetative growth and tillering potential, as also reported by Khanum *et al.* (2023) and Zi *et al.* (2025). These results further corroborate that both genotype and nutrient management interactively determine growth performance under site-specific conditions.

Yield attributes of *boro* rice

The number of filled grains per panicle, unfilled grains per panicle, panicle length, and thousand-grain weight of *boro* rice were significantly influenced by variety, sulphur level, and their interaction (Table 1). Among the varieties, *Hira-2* (Hybrid) outperformed all in terms of filled grains per panicle (323.0), grain weight (28.79 g), and lowest sterility (0.20 unfilled grains per panicle), highlighting the advantage of hybrid vigor. In contrast, BRRI dhan28 consistently exhibited the poorest performance with the lowest filled grains (91.5), shortest panicle (18.3 cm), highest sterility (19.3 unfilled grains), and lowest grain weight (21.8 g). BRRI dhan89 and BRRI dhan29 performed intermediately, with BRRI dhan89 recording the longest panicle (22.7 cm), reflecting genetic variation in panicle development and sink capacity. Sulphur fertilization significantly improved filled grains per panicle, panicle length, and grain weight, though it did not reduce sterility (Table 2). The 1.5× recommended sulphur dose

(T_3) was most effective, producing the longest panicles (22.0 cm) and the highest TGW (25.31 g), while the control (T_0) produced the lowest values. This suggests that sulphur plays a crucial role in assimilate translocation and grain filling. However, sterility was primarily variety-dependent, as observed by the consistently high unfilled grains in BRRI dhan28 irrespective of sulphur treatment, whereas *Hira-2* maintained near-zero sterility across all treatments. Variety × Sulphur interaction further emphasized this differential responsiveness (Table 3). The maximum filled grains (335.7) were obtained in *Hira-2* × T_1, while BRRI dhan28 × T_0 had the lowest (89.0). Unfilled grains were highest in BRRI dhan28 × T_0 (22.0) but completely absent in *Hira-2* × T_2 and T_4. The longest panicle (23.7 cm) was recorded in BRRI dhan89 × T_3, while the shortest (12.7 cm) was in BRRI dhan28 × T_0. Similarly, the heaviest grains (29.37 g) were produced by *Hira-2* × T_3. These findings underscore that hybrid and modern varieties with strong sink capacity respond better to sulphur application than inbred, short-duration cultivars like BRRI dhan28. The superiority of hybrids over inbred varieties observed here aligns with the findings of Banu *et al.* (2014) and Akter *et al.* (2014), who reported higher grain yield and improved grain filling in hybrid *Hira* compared to BRRI dhan28 and BRRI dhan29. Similarly, Khanum *et al.* (2023) found that hybrid *Hira-5* produced 8.81 t $^{-1}$ grain yield, significantly higher than BRRI dhan28 (6.40 t ha^{-1}). The present results are also consistent with international studies (Jiang *et al.*, 2015; Yan *et al.*, 2025; Zi *et al.*, 2025) showing hybrids outperform inbreeds in terms of spikelets per panicle, grain filling, and TGW due to higher sink size and nutrient use efficiency. Comparing with earlier findings in Bangladesh, Salwa *et al.* (2020) reported that BRRI dhan28 and BRRI dhan29 produced 105–162 grains panicle^{-1} and 1000-grain weights around 21–23 g under recommended fertilizer management. In the present study, however, BRRI dhan28 recorded much lower filled grains (91.5) but comparable grain weight (21.8 g), while BRRI dhan29 showed higher filled grains (190.6) and heavier grains (25.0 g). These differences may be due to varietal aging, environmental stress in the *haor*, or differential response to sulphur. Likewise, Dey *et al.* (2025) noted that BRRI dhan92 and BRRI dhan29 had more than 145 filled grains panicle^{-1}, comparable to our findings for BRRI dhan29, but significantly lower than *Hira-2*, which confirms the superior genetic potential of hybrids in *haor* conditions. Panicle length also varied with genotype. BRRI dhan89 (22.7 cm) and *Hira-2* (20.7 cm) produced longer panicles than BRRI dhan28, in agreement with Akter *et al.* (2025), who reported varietal differences in panicle length across BRRI dhan29, BRRI dhan58, and BRRI dhan92. In our study, sulphur fertilization, especially T_3, enhanced panicle elongation, which corroborates findings that nutrient management can improve panicle size and spikelet fertility. Overall, the results confirm that varietal selection remains the key driver for improving yield components in the *haor*, with hybrid *Hira-2* clearly superior. Sulphur fertilization, particularly at 1.5× the recommended dose, further enhanced grain weight and panicle traits, but could not offset the high sterility observed in BRRI dhan28. These findings align with both national (Salwa *et al.*, 2020; Dey *et al.*, 2025; Akter *et al.*, 2025) and international studies (Jiang *et al.*, 2015; Yan *et al.*, 2025), highlighting the combined role of genetic potential and nutrient management in optimizing rice productivity in flood-prone *haor* areas.

Table 3. Interaction effect of variety and sulphur on growth and yield attributes of *boro* rice.

Interaction (V×T)	Plant Height at Harvest	Number of total tillers hill^{-1}	Number of effective tiller hill^{-1}	Number of non -effective tiller hill^{-1}	Number of filled grain per panicle	Number of unfilled grain panicle	Panicle length (cm)	Thousand-grain weight (g)
V_1×T_0	83.00±2.00h	15.67±2.08h	15.33±2.52g	0.33±0.57ab	89.0±1.0i	22.0±2.65a	12.67±1.53g	22.00±0.26f
V_1×T_1	94.90±1.21e-g	19.33±0.57e-g	19.33±0.57ef	0.00±0.00b	93.0±2.65hi	18.67±4.04a-c	19.67±2.52def	21.90±0.46f
V_1×T_2	91.00± 1.0g	21.00±1.0de	20.67±2.52de	0.33±0.57ab	91.0±3.46i	21.0±4.36ab	20.67±3.06a-f	21.70±0.40f
V_1×T_3	91.33± 2.08fg	20.67±2.52de	20.67±2.52de	0.00±0.00b	93.67±1.53hi	18.33±3.51a-d	20.00±1.00c-f	21.73±0.58f
V_1×T_4	95.70±1.55d-g	20.0±2.0ef	19.67±1.52ef	0.33±0.57ab	91.0±1.0i	17.67±3.79a-e	18.33±3.21f	21.50±0.26f
V_2×T_0	79.59±3.88h	13.0±1.0i	12.33±1.0h	0.67±0.57b	104.0±4.58g	17.0±2.65b-f	20.00±1.00c-f	24.63±0.61c-e
V_2×T_1	80.86±7.66h	17.0±1.0gh	17.0±1.53fg	0.00±0.00b	114.67±4.16f	13.67±4.04d-f	22.33±1.52a-e	25.07±0.15cd
V_2×T_2	76.79±2.22h	16.0±1.0h	15.67±2.0g	0.33±0.57ab	115.0±1.0f	15.33±3.79c-f	21.00±2.00a-f	24.97±0.38c-e
V_2×T_3	78.74±1.92h	16.33±1.5h	16.0±1.15g	0.33±0.57ab	112.0±4.58fg	13.33±3.51ef	22.67±1.53a-d	25.33±0.65c
V_2×T_4	80.09±2.30h	17.67±1.53f-h	17.33±1.0fg	0.33±0.57ab	102.33±1.53gh	12.67±3.79f	22.33±1.53a-e	25.23±0.55cd
V_3×T_0	103.55±4.52a-c	22.67±1.15cd	22.67±2.65cd	0.00±0.00b	159.67±5.51e	4.67±1.53gh	21.33±1.53a-f	24.57±0.47c-e
V_3×T_1	107.70±9.29ab	28.0±1.0a	28.0±1.0a	0.00±0.00b	176.0±2.59d	3.67±0.57gh	23.33±1.53ab	24.70±0.95c-e
V_3×T_2	104.14±4.09a-c	27.0±2.65ab	27.0±0.57ab	0.00±0.00b	172.67±8.02d	4.0±0.57gh	22.00±2.20a-e	23.97±0.50e
V_3×T_3	108.63±5.68a	23.0±1.0cd	23.0±1.0cd	0.00±0.00b	172.33±2.89d	3.33±0.57gh	23.67±1.53a	24.80±0.52c-e
V_3×T_4	109.64±2.80a	25.0±1.0bc	25.0±1.0bc	0.00±0.00b	171.0±5.57d	5.33±0.57ge	23.00±1.00a-c	24.30±0.40de
V_4×T_0	96.77±2.68c-g	7.67±0.57k	7.67±0.57i	0.00±0.00b	305.0±5.0c	0.33±0.00h	19.33±1.00ef	28.80±0.26ab
V_4×T_1	102.62±1.83a-d	11.0±1.73ij	11.0±1.73h	0.00±0.00b	335.7±17.6a	0.33±0.57h	21.33±1.53a	28.87±0.35ab
V_4×T_2	100.25±3.03b-e	10.0±2.65jk	10.0±2.65hi	0.00±0.00b	328.33±7.02ab	0.00±0.00h	20.33±2.08b-f	28.60±0.70ab
V_4×T_3	102.70±6.19a-d	10.0±1.0jk	10.0±1.0hi	0.00±0.00b	320.0±4.58b	0.33±0.57h	21.67±1.53a-e	29.37±0.51a
V_4×T_4	98.806±1.10c-f	10.0±1.0jk	10.0±1.0hi	0.00±0.00b	326.0±7.55ab	0.00±0.00h	21.00±1.00a-f	28.33±0.70b
CV	4.36	8.38	9.03	259.04	3.39	27.83	7.42	2.12
Level of Sig.	**	***	***	*	*	*	*	*

Values are presented as mean ± standard error. Means within a column followed by different letters (a–i) differ significantly at the 5% level of probability according to Duncan's Multiple Range Test (DMRT). CV = Coefficient of Variation. Level of significance: ns = non-significant, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. V_1= BRRI dhan 28, V_2= BRRI dhan 29, V_3= BRRI dhan 89 and V_4= *Hira-2* (Hybrid), T_0=No fertilizer, T_1= Recommended rate of fertilizer Urea, TSP, MOP, Gypsum, and ZnSO4 @ 260 Kg ha^{-1}, 100 Kg ha^{-1}, 120 Kg ha^{-1}, 110 Kg ha^{-1} and 11 Kg ha^{-1}, T_2= Recommended rate + Half of recommended dose sulphur fertilizer (55 Kg ha^{-1}), T_3= Recommended rate + One and half of recommended dose sulphur fertilizer (165 Kg ha^{-1}), and T_4= Recommended rate + Double of recommended dose sulphur fertilizer (220 Kg ha^{-1}).

Grain yield, straw yield, biological yield, and harvest index

The performance of *boro* rice varieties varied significantly for yield, and yield components. Among the four studied varieties, the hybrid *Hira-2* (V_4) produced the highest grain yield (9.24 t ha^{-1}), biological yield (14.69 t ha^{-1}), and harvest index (62.89%), significantly outperforming the inbred lines BRRI dhan28 (V_1), BRRI dhan29 (V_2), and BRRI dhan89 (V_3) (Figure 3). This confirms the superior performance of hybrid rice under the *haor* conditions, consistent with previous studies showing hybrids generally outperform inbred varieties due to enhanced photosynthetic efficiency, tillering ability, and source-sink dynamics (Muralidharan *et al.*, 2012; Akter *et al.*, 2014; Haque *et al.*, 2015; Salwa *et al.*, 2019, 2020; Khanum *et al.*, 2023). Similarly, high-yielding japonica hybrid cultivars exhibited more spikelets per panicle, greater panicle length, and higher harvest index compared to inbred lines (Chen *et al.*, 2025). Among inbred varieties, BRRI dhan89 (V_3) and BRRI dhan29 (V_2) showed superior yield and yield-contributing traits relative to BRRI dhan28 (V_1). BRRI dhan29 consistently produced higher grain yield (6.11 t ha^{-1}) and filled grains per panicle (145.07), while BRRI dhan28 recorded lower grain yield (5.50 t ha^{-1}) and filled grains (Salwa *et al.*, 2019; Dey *et al.*, 2025). These results align with earlier findings indicating that short-duration high-yielding varieties like BRRI dhan28 are prone to yield limitations under stress conditions such as flash floods and cold stress during the reproductive stage (Dey *et al.*, 2025; Akter *et al.*, 2025). Sulphur fertilization had a significant positive effect on grain yield, straw yield, biological yield, and harvest index ($p < 0.001$) (Figure 4). Grain yield increased progressively with increasing sulphur levels, reaching a maximum at T_3 (165 kg S ha^{-1}) with 7.42 t ha^{-1}, while T_4 (220 kg S ha^{-1}) did not produce significant additional benefits, indicating a plateauing effect at higher sulphur doses. Similar patterns were observed for straw yield, biological yield, and harvest index. These results support previous studies highlighting the role of sulphur in promoting chlorophyll synthesis, protein formation, and overall plant metabolism, thereby enhancing grain development (Bassiouni *et al.*, 2016; Kalala *et al.*, 2016; Bari *et al.*, 2023).

The interaction between variety and sulphur level (V×T) was significant for biological yield ($p < 0.001$) and moderately significant for grain yield, straw yield, and harvest index (Table 4). The highest productivity was recorded in V_4T_3 (*Hira-2* hybrid with 165 kg S ha^{-1}), producing 9.56 t ha^{-1} grain yield, 14.73 t ha^{-1} biological yield, and 64.94% HI. Conversely, the lowest grain yield (4.36 t ha^{-1}) was observed in V_1T_0 (BRRI dhan28 without sulphur fertilization), highlighting the critical role of both genotype and nutrient management. Among inbred lines, BRRI dhan89 (V_3) demonstrated consistent yield improvement with sulphur fertilization, indicating good sulphur responsiveness, while BRRI dhan28 and BRRI dhan29 showed moderate responses (Kamruzzaman & Uddin, 2020). The significant V×T interactions observed in this study align with earlier findings, which report that hybrid varieties often exhibit higher nutrient uptake and utilization efficiency compared to inbred varieties, resulting in greater responsiveness to sulphur application (Salwa *et al.*, 2019; Akter *et al.*, 2025; Zi *et al.*, 2025). Similar patterns have been observed in other hybrid rice studies where maximum yields were achieved when high-yielding hybrids were combined with optimal nutrient management (Giri *et al.*, 2025).

Table 4. Interaction effect of variety and sulphur levels on grain yield, straw yield, biological yield, and harvest index of *boro* rice in *haor* areas of Bangladesh.

Interaction (V×T)	Grain Yield (t/ha)	Straw Yield (t/ha)	Biological Yield (t/ha)	Harvest Index (%)
$V_1×T_0$	4.36±0.15j	6.36±0.15g	10.36±0.09j	42.16±1.86g
$V_1×T_1$	5.30±0.20i	7.96±0.75def	10.65±0.06i	49.75±2.19e
$V_1×T_2$	5.23±0.25i	8.23±0.25de	10.87±0.16h	48.12±2.09ef
$V_1×T_3$	5.36±0.46i	7.96±0.23def	10.72±0.24hi	50.07±4.96e
$V_1×T_4$	5.50±0.26hi	7.73±0.47efg	11.06±0.01g	49.69±2.35e
$V_2×T_0$	5.80±0.30h	7.10±0.30g	12.88±0.04f	45.00±2.26fg
$V_2×T_1$	6.40±0.10g	7.56±0.15fg	12.91±0.08f	49.56±1.06e
$V_2×T_2$	6.20±0.20g	7.26±0.20g	12.93±0.01f	47.94±1.53ef
$V_2×T_3$	6.43±0.42g	7.36±0.45fg	12.95±0.01f	49.67±3.23e
$V_2×T_4$	6.43±0.32g	7.60±0.52e-g	13.07±0.01f	49.22±2.49e
$V_3×T_0$	7.20±0.10f	8.40±0.26cd	13.44±0.17e	53.54±1.06d
$V_3×T_1$	7.70±0.10e	8.86±0.15bc	13.41±0.22e	57.42±1.19c
$V_3×T_2$	8.16±0.15d	9.13±0.15b	13.64±0.06d	59.87±1.17bc
$V_3×T_3$	8.33±0.21d	9.30±0.10b	13.82±0.22d	60.29±0.86bc
$V_3×T_4$	8.43±0.25d	9.27±0.21b	14.10±0.02c	59.80±1.71bc
$V_4×T_0$	8.93±0.15c	10.30±0.50a	14.58±0.02b	61.26±1.02ab
$V_4×T_1$	9.10±0.10bc	10.37±0.47a	14.58±0.06a	62.38±0.92ab
$V_4×T_2$	9.40±0.10ab	10.37±0.21a	14.65±0.10b	64.14±0.69a
$V_4×T_3$	9.56±0.15a	10.50±0.10a	14.73±0.02ab	64.94±0.98a
$V_4×T_4$	9.20±0.10a-c	10.53±0.21a	14.90±0.09a	61.74±0.79ab
CV	3.26	4.03	0.83	3.75
Level of sig.	*	*	***	**

Values are expressed as mean ± standard error. Means within a column followed by different letters (a–j) differ significantly at the 5% level of probability according to Duncan's Multiple Range Test (DMRT). CV = Coefficient of Variation. Level of significance: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. V_1= BRRI dhan 28, V_2= BRRI dhan 29, V_3= BRRI dhan 89 and V_4= *Hira-2* (Hybrid), T_0=No fertilizer, T_1= Recommended rate of fertilizer Urea, TSP, MOP, Gypsum and ZnSO4 @ 260 Kg ha^{-1}, 100 Kg ha^{-1}, 120 Kg ha^{-1}, 110 Kg ha^{-1} and 11 Kg ha^{-1}, T_2= Recommended rate + Half of recommended dose sulphur fertilizer (55 Kg ha^{-1}), T_3= Recommended rate + One and half of recommended dose sulphur fertilizer (165 Kg ha^{-1}), and T_4= Recommended rate + Double of recommended dose sulphur fertilizer (220 Kg ha^{-1}).

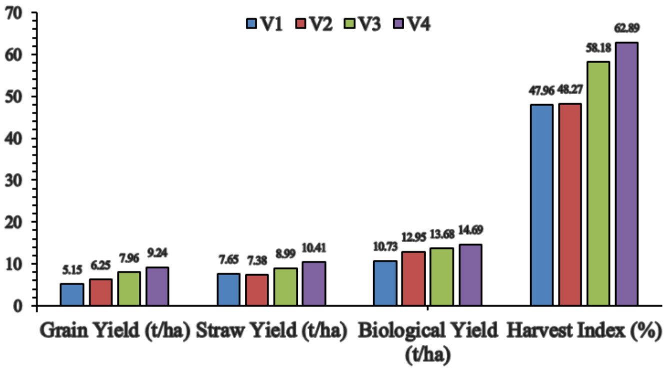

Figure 3. *Effect of variety on grain yield, straw yield, biological yield, and harvest index of Boro rice in the haor areas of Bangladesh. [V_1= BRRI dhan 28, V_2= BRRI dhan 29, V_3= BRRI dhan 89 and V_4= Hira-2 (Hybrid)].*

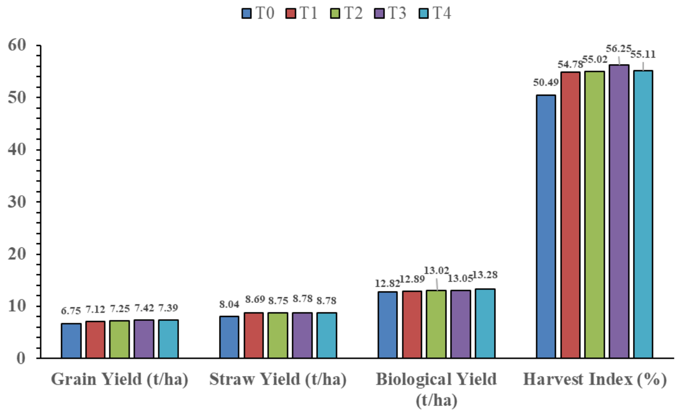

Figure 4. *Effect of different sulphur levels on grain yield, straw yield, biological yield, and harvest index of boro rice in the haor areas of Bangladesh.[T_0=No fertilizer, T_1= Recommended rate of fertilizer Urea, TSP, MOP, Gypsum and ZnSO4 @ 260 Kg ha^{-1}, 100 Kg ha^{-1}, 120 Kg ha^{-1}, 110 Kg ha^{-1} and 11 Kg ha^{-1}, T_2= Recommended rate + Half of recommended dose sulphur fertilizer (55 Kg ha^{-1}), T_3= Recommended rate + One and half of recommended dose sulphur fertilizer (165 Kg ha^{-1}), and T_4= Recommended rate + Double of recommended dose sulphur fertilizer (220 Kg ha^{-1})].*

Overall, the study confirms that hybrid varieties, particularly *Hira-2* and other high-yielding lines, are superior to inbred *boro* rice varieties in terms of yield, yield components, and responsiveness to sulphur fertilization. The observed improvements in grain yield and harvest index are supported by multiple studies showing that hybrids outperform inbred cultivars due to larger panicle size, higher tillering capacity, and better source-sink dynamics (Jiang *et al.*, 2015; Salwa *et al.*, 2020; Yan *et al.*, 2025). The findings also highlight the importance of site-specific nutrient management, as sulphur requirements in *haor* areas were higher than recommended doses reported in other regions (Bari *et al.*, 2023), likely due to frequent flooding and nutrient leaching. Therefore, maximizing rice productivity in the *haor* region requires an integrated approach involving high-yielding hybrid varieties, appropriate sulphur application, and timely management practices (Akter *et al.*, 2025; Dey *et al.*, 2025).

Multivariate analysis of growth and yield traits using Principal Component Analysis (PCA)

The PCA biplot (Figure 5) illustrates the multivariate relationship among rice genotypes and their associated growth and yield traits. The first two principal components explained 84.2% of the total variability, with Dim1 accounting for 65.7% and Dim2 contributing 18.5%. Grain yield, straw yield, biological yield, harvest index, filled grains per panicle, and thousand grain weight showed strong positive loadings along Dim1, clearly separating Hybrid *Hira-2* genotypes toward the positive axis. This indicates that Hybrid *Hira-2* was strongly associated with higher yield-related attributes, reflecting its superior productivity potential. In contrast, BRRI dhan28 and BRRI dhan29 were clustered toward the negative side of Dim1, showing association with traits such as tiller number per hill and moderate plant height, but lower contribution from yield-related traits. BRRI dhan89 grouped near the center of the biplot, suggesting intermediate performance across most traits. Trait vectors positioned closely together, such as grain yield, straw yield, and biological yield, confirmed their strong positive interrelationship, whereas vectors pointing in opposite directions, such as tiller number versus thousand grain weight, suggested trade-offs among traits. Overall, the PCA biplot revealed that yield variability among genotypes was primarily explained by the combined effects of biomass-related traits (straw and biological yield) and grain parameters (filled grains per panicle and thousand-grain weight). This multivariate analysis provides valuable insight for breeders, indicating that Hybrid *Hira-2* possesses a distinct advantage in yield-contributing traits, while BRRI dhan28 and BRRI dhan29 may serve as useful sources for tillering capacity.

Correlation among growth and yield-contributing traits of rice

The correlation matrix (Figure 6) revealed strong positive and significant associations among most of the studied yield and yield-contributing traits. Grain yield exhibited a very high positive correlation with biological yield (r = 0.93), straw yield (r = 0.91), and harvest index (r = 0.79), suggesting that improvement in these parameters can directly enhance grain productivity. Similarly, straw yield also showed significant positive correlations with biological yield (r = 0.96) and harvest index (r = 0.75). Plant height demonstrated moderate positive correlations with grain yield (r = 0.68), straw yield (r = 0.74), and biological yield (r = 0.62), indicating that taller plants generally tended to perform better in terms of biomass and yield. However, panicle length showed weak to moderate negative correlations with plant height (r = –0.54) and straw yield (r = –0.65), suggesting a possible trade-off between panicle development and vegetative growth. Overall, the strong interrelationships among grain yield, straw yield, biological yield, and harvest index highlight their importance as reliable selection criteria in rice breeding and management practices. These findings are consistent with earlier studies (Akter *et al.*, 2014; Haque *et al.*, 2015; Khanum *et al.*, 2023), which reported similar correlations among yield components in rice.

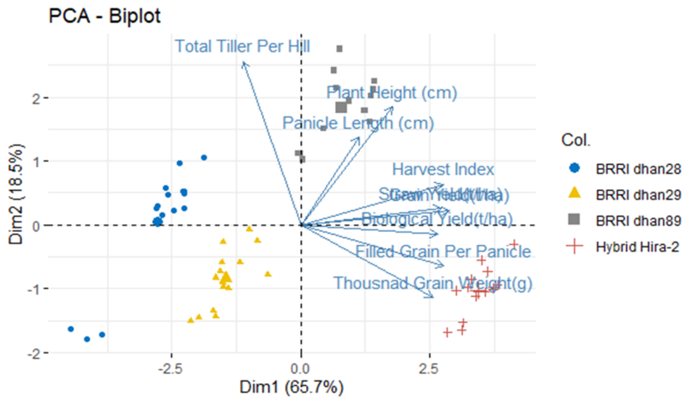

Figure 5. *PCA biplot showing the relationship among rice genotypes and key growth and yield traits.*

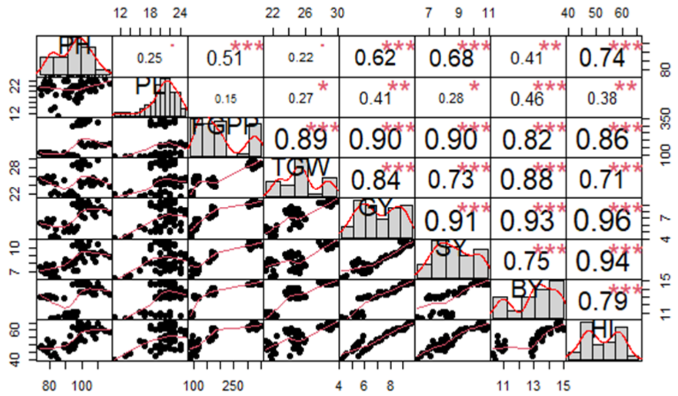

Figure 6. *Correlation matrix (pairs plot) showing the relationship among growth, yield, and yield-attributing traits of rice. (PH = Plant Height, PL = Panicle length (FGPP = Filled Grain Per Panicle, TGW = Thousand Grain Weight, GY = Grain Yield, SY = Straw Yield, BY = Biological Yield and HI = Harvest Index).*

Conclusion

This study demonstrated that rice variety and sulphur application significantly influence *boro* rice yield in *haor* areas. The hybrid variety *Hira-2* showed the highest grain yield (9.24 t ha^{-1}), while BRRI dhan28 had the lowest. Optimal sulphur application (165 kg S ha^{-1}) significantly enhanced growth and yield attributes, with the highest yield (7.42 t ha^{-1}) observed at this level. The interaction of variety and sulphur level was also significant, with *Hira-2* at 165 kg S ha^{-1} achieving the highest yield (9.56 t ha^{-1}). Selecting high-yielding varieties and optimizing sulphur levels can enhance rice productivity in *haor* regions. Future studies should explore multi-location and long-term evaluations of sulphur fertilization and varietal responses to optimize nutrient management, yield stability, and sustainability of *boro* rice production in the *haor* ecosystem.

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DECLARATIONS

Author contribution statement: Conceptualization: M.T.I; Methodology: M.T.I; Software and validation: M.T.I., F.T.Z.H. and H.I.; Formal analysis and investigation: M.T.I.; Resources: M.T.I.; Data curation: M.T.I; Writing—original draft preparation: M.T.I.; Writing—review and editing: M.Z.; Visualization: F.T.Z.H.; Supervision: M.T.I.; Project administration: M.T.I.; Funding acquisition: M.T.I All authors have read and agreed to the published version of the manuscript.

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Ethics approval: This study did not involve any animal or human participant and thus ethical approval was not applicable.

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