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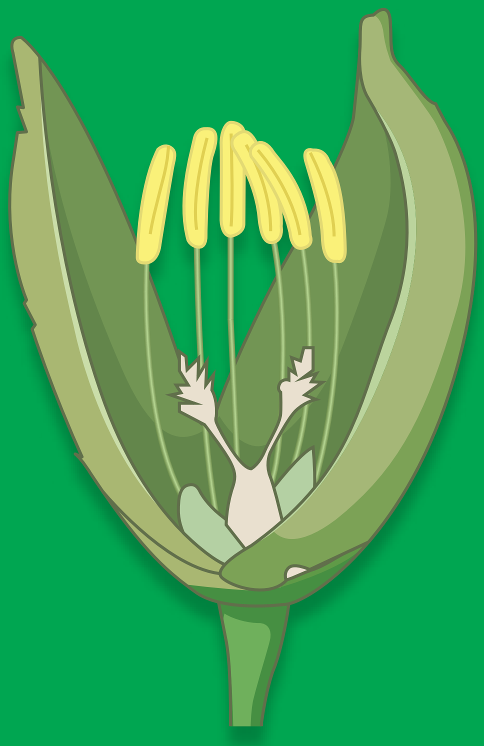

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Breeding for Resilience: Cross-Environment Stability of Rice Genotypes Combining High Yield and Major Disease Resistance

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ABSTRACT

Rice production is severely affected by different stresses, especially biotic stresses. The current study was aimed to identify resilient genotypes with wider adaptation along with major disease resistance. Genotypes, BR11866-5R-277, BR11867-5R-118, BR11867-5R-331, BR12437-4R-164, BRRI dhan101, and BRRI dhan89 were identified as the most stable genotypes by utilizing GGE biplot and PCA analysis, whereas BR11869-5R-148, BR12125-6R-6, BR12125-6R-79, and BR13796-5R-102 exhibited site-specific adaptability for grain yield. MGIDI index demonstrated that BR11866-5R-277, BR11867-5R-331, and BRRI dhan89 were closest to the ideotype by combining multi-trait i.e., yield, growth duration, and plant height, with stability. Most of the genotypes met the national standard of grain quality. The genotypes BR11866-5R-277 and BR11867-5R-331 showed BB resistance and BR11867-5R-118, BR12125-6R-6, BR12125-6R-79, BR12450-4R-108, BR12450-4R-24 demonstrated blast resistance. The genotypes BR11866-5R-277 and BR11867-5R-119 showed resistance to BB and blast both. Based on SNP genotyping and screening result different combinations of pyramided lines were identified. Those lines will be the potential donors for further breeding program. The genotypes BR11866-5R-277, BR11867-5R-118, BR11867-5R-331, BR12125-6R-6, BR12450-4R-108, and BRRI dhan101 could be promising candidates for breeding program targeting high yield, stability, superior quality, and durable disease resistance. The BR11866-5R-277 and BR11867-5R-331 line would be selected for further trial and variety release for bacterial blight (BB) and tungro (RTV) resistance, respectively.

1. Introduction

Rice (*Oryza sativa* L.) is an important staple food for over half of the global population and plays a vital role in food security and nutrition, especially in Asia (Fukagawa et al., 2019). In Bangladesh, food and nutritional security are synonymous to rice production. However, rice production is continually threatened by several types of biotic stresses, particularly bacterial blight (BB), blast, and rice tungro disease, which collectively account for significant yield losses in many rice-growing areas.

Bacterial blight, spread by *Xanthomonas oryzae* pv. *oryzae (Xoo)*, is one of the most detrimental rice

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diseases, causing 50% yield losses in epidemic condition (Iqbal et al., 2023; Fiyaz et al., 2022). *Magnaporthe oryzae* is the cause of blast disease, which is similarly deadly. It attacks crops at any growth stages, but most detrimental at flowering to early maturity. In a favorable environment, it causes even 100% yield loss in susceptible varieties (Pedrozo et al., 2025; Wang et al., 2014). Tungro disease, caused by a complicated combination of *rice tungro bacilliform virus (RTBV)* and *rice tungro spherical virus (RTSV)*, is an additional limitation in tropical Asia, that leads to stunted growth and significant yield reductions (Dey et al., 2024; Bunawan et al., 2014). Significant progress has been achieved in disease resistance breeding by discovering and deploying of resistance genes like *Xa21, Xa5* and *Xa13* for BB; *Pi9, Pita* and *Pb1* for blast; and *TSV1* & *TBV1* for tungro (Fiyaz et al., 2022; Latif et al., 2025; Widiarta et al., 2025). Nevertheless, the durability of resistant genotypes is hampered by the evolution of noble isolates of the pathogen and climate change by the overcoming of the resistance (Michelmore et al., 2013).

Therefore, the modern disease resistance breeding strategies must be prioritized, combining higher yield potentials and broad-spectrum resistance to BB, blast, and tungro across diverse environments. Such integrated breeding strategies must be tested in multiple environments for improving yield, resilience and protecting rice from diverse biotic challenges.

Genotype-environment interaction (GEI) has a considerable impact on the performance and stability of each of the production and resistance traits, challenging the selection process in breeding programs (Egea-Gilabert et al., 2021). GEI represents the genotype-environment reaction in terms of adaptation. Cross-environment stability enables breeders to find out resilient cultivar that performs consistently in diverse environments, specially having the potentiality to adapt in climate change (Justo et al., 2024).

GGE biplot analysis is one of the typical statistical methods to detect GEI of target traits across multiple environments. GGE biplots graphically represent the GEI of numerous environments that facilitate quick and easier evaluation of genotypes. GGE biplots illustrate the first and second principal components by single value decomposition of environment-centered multiple environment trial data to evaluate genotypes and mega-environment identification (Yan et al., 2000). A newer technique called WAASB is used to assess quantitative genotypic stability, the weighted average of absolute scores from the singular value decomposition of the matrix of best linear unbiased predictions (BLUP), for GEI effects obtained in a linear mixed model (LMM) (Olivoto et al., 2019)

In this context, the current study seeks to assess the stability and adaptation of rice genotypes with major diseases, particularly bacterial blight, blast & tungro, and high yield potential across multi-environmental conditions. The study also sheds light on the interactions between genotype, environment, and resistance expression, which will aid in the development of robust rice varieties that contribute to food security for sustainable agriculture.

2. Materials and methods

2.1. Plant materials

A total of 17 rice genotypes including, three check varieties, were used for field experiments. The complete set and details of genotypes used in the study are summarized in Table 1.

Table 1
Status and designation of the advanced breeding lines and check varieties of rice.

Genotypic code	Designation	Parentage	Remarks
G1	BR11866-5R-277	HHZ23-DT16-DT1-DT1/BP10620F-BB-4-17-BB8	Advanced Line
G2	BR11867-5R-118	BRRI dhan75/BP10620F-BB-4-17-BB8	Advanced Line
G3	BR11867-5R-119	BRRI dhan75/BP10620F-BB-4-17-BB8	Advanced Line
G4	BR11867-5R-331	BRRI dhan75/BP10620F-BB-4-17-BB8	Advanced Line
G5	BR11869-5R-148	BR8938-19-4-3-1-1/Habataki	Advanced Line
G6	BR12125-6R-149	BRRI dhan63*3/IR93323//IRBB60/N22	Advanced Line
G7	BR12125-6R-6	BRRI dhan63*3/IR93323//IRBB60/N22	Advanced Line
G8	BR12125-6R-79	BRRI dhan63*3/IR93323//IRBB60/N22	Advanced Line
G9	BR12437-4R-109	BRRI dhan58*2/IRBB60	Advanced Line
G10	BR12437-4R-164	BRRI dhan58*2/IRBB60	Advanced Line
G11	BR12450-4R-108	BRRI dhan29/IRBL9-W(RL)(Pi9)	Advanced Line
G12	BR12450-4R-24	BRRI dhan29/IRBL9-W(RL)(Pi9)	Advanced Line
G13	BR13790-5R-216	BRRI dhan29*3/Pb1[US]	Advanced Line
G14	BR13796-5R-102	BRRI dhan64*2/pi21 [US]	Advanced Line
G15	BRRI dhan101		Resistant check
G16	BRRI dhan88		Susceptible & Standard check
G17	BRRI dhan89		Susceptible & Standard check

2.2. Locations and field experimental design

Seventeen rice genotypes were evaluated at the Regional Stations, namely, Rajshahi, Rangpur, Kushtia, Cumilla, Bhanga, Sonagazi, Satkhira, Habiganj, and Gazipur in Bangladesh Rice Research Institute (BRRI) (Table 2). The areas were chosen specifically because of their excellent potential for rice cultivation and the field trial was conducted in Boro season, 2023-24. The studies in all locations were set up in a randomized complete block design (RCBD) with two replications. The plot dimensions were 5 m × 2 m, with plants spaced 20 cm apart in rows and plant to plant. Seedlings were transplanted 30-40 days after sowing, with one seedling per hill to maintain the line purity. Gap filling was carried out within two weeks after transplanting, to ensure homogeneous growth of the crop. Fertilizer was applied at the BRRI recommended rate (three instalments as top dressing). The first and second applications were completed during the tillering and booting stages, respectively. Weed, insect, and disease control were implemented as advised for the crop, utilizing an integration of chemical and cultural approaches. During crop development, additional irrigation was applied to maintain enough soil moisture in each plot.

Table 2
List of experimental locations with assigned environmental codes.

Locations	Locations/Environmental code
Satkhira	E1
Sonagazi	E2
Bhanga	E3
Cumilla	E4
Gazipur	E5
Habiganj	E6
Kushtia	E7
Rajshahi	E8
Rangpur	E9

2.3. Measurement of the traits

Three yield and yield attributing traits, namely plant height (PH; cm), growth duration (GD; days), and grain yield (YLD; t/ha), were measured across all location environments. PH was determined by measuring upper ground height of 10 plants and measured mean plant height in centimeters (cm). The entire plot in each replication was harvested to determine grain yield (YLD), which was expressed in t/ha. The distribution patterns of collected data are shown in Fig. 1.

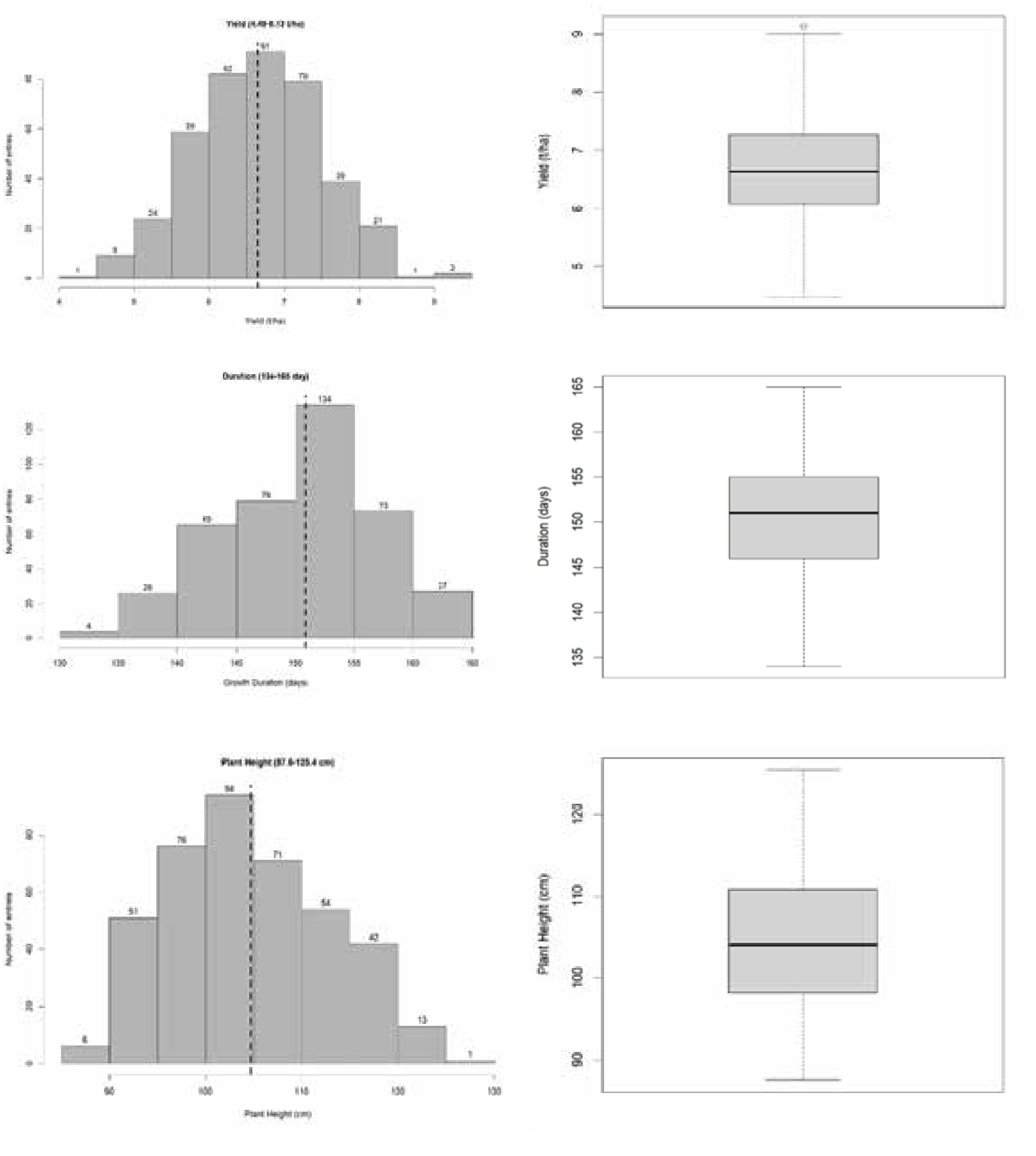

Fig. 1. Histogram and boxplot of grain yield, growth duration and plant height. Dot vertical line in histogram represent population mean and bold horizontal line in boxplot represent the population mean.

2.4. Statistical analyses

All statistical analyses were done by using R Studio version 2024.12.0. Utilizing the 'Agricolae' program, a combined ANOVA was performed to investigate the presence of GEI employing a complete dataset of studies across nine environments (Mendiburu, 2020). Agronomic performance of each genotype in each environment and combine performance was calculated in the best linear unbiased estimation model (BLUE) and predicted performance was calculated in best linear unbiased prediction model (BLUP) using R package lmerTest (Kuznetsova et al., 2017), emmeans (Lenth, 2025), pbkrtest (Halekoh & Højsgaard, 2014). Correlation of yield and yield contributing traits and the environment were calculated using the metan package (Olivoto & Lúcio, 2020). Principal component analysis was done using the factoextra package (Kassambara & Mundt, 2017).

Adaptability of genotypes and mega-environments (MEs), a group of environments that share the same winning genotypes, in the nine different environments, trials were evaluated using genotypic main effect plus GEI (GGE) biplot analysis (Yan et al., 2002), using the 'metan' package (Olivoto & Lúcio, 2020). Environments were evaluated using the 'discriminativeness vs. representativeness' view of the GGE biplot. MEs and winner genotypes in a given set of environments were identified using a 'which-won-where' GGE biplot. Adaptability of genotypes to multi-environments was evaluated using a 'ranking genotypes' GGE biplot, comparing the ideal genotypes, which were defined as showing the highest performance in all environments. To evaluate the yield stability of genotypes across environments a mean vs stability GGE biplot was created. For calculating the multi-trait stability index, the WAASBY index (Olivoto et al., 2019), a superiority index that allows weighting between performance and stability (WAASB), was calculated to identify genotypes that combined high agronomic value with stability. Multitrait Genotype-Ideotype Distance Index (MGIDI) was calculated using "metan" package for selecting Ideal genotype (Debnath et al., 2024).

3. Results

3.1. Variation and agronomic performance of grain yield and its components for multiple environments

In Regional Yield Trial (RYT), 17 rice genotypes were investigated across nine agro-climatic zones in Bangladesh to identify suitable genotype adaptation for yield, plant height, growth duration and disease resistance. Temperature, relative humidity, and precipitation varied significantly throughout the test sites. ANOVA revealed extremely significant main effects of genotype (G), environment (E), and genotype-by-environment interaction (GEI) for all evaluated traits (Table 3). The replication effects were non-significant for the variables except growth duration.

Table 3

Combined Analysis of Variance of yield and yield contributing characters.

Sources of variation	Df	YLD		PH		GD	
		MS	Pr(>F)	MS	Pr(>F)	MS	Pr(>F)
REP	2	0.11	0.52^{NS}	7.72	0.07^{NS}	68.83	3.837e-15 ***
GEN	16	2.42	<2e-16 ***	860.57	< 2e-16 ***	363.22	< 2.2e-16 ***
ENV	8	13.26	<2e-16 ***	795.34	< 2e-16 ***	1194.60	< 2.2e-16 ***
GEN: ENV	128	0.75	<2e-16 ***	59.35	< 2e-16 ***	13.34	< 2.2e-16 ***
Residuals	253	0.17		2.95		1.81	

GEN = Genotypes, ENV = Environment, GEN: ENV = Genotype-environment interaction, REP = Replication, YLD = Grain Yield (t/ha), PH = Plant Height (cm), GD = Growth Duration (days)
*** = 0.1% level of significance, ** = 1% level of significance, * = 5% level of significance

The average grain yield varied from 4.56 to 8.71 t/ha, with a least significant difference (LSD, $p < 0.05$) of 0.51 t ha^{-1}. Using both best linear unbiased estimates (BLUE) and best linear unbiased predictions (BLUP), genotypes G1, G2, and G15 consistently performed well. Rangpur and Bhanga were identified as the most favorable environments, producing average yields 13.38% and 10.6% higher than the grand mean, respectively (Table 4). The other agronomic traits, such as growth duration and plant height, are favorable, indicating its potential as a promising line for use as a parent or variety (Table S1 & Table S2).

Table 4

Best Linear Unbiased Estimation (BLUE) and Best Linear Unbiased Prediction (BLUP) Based Yield (t/ha) performance of tested genotype.

Gen	E1	E2	E3	E4	E5	E6	E7	E8	E9	pBLUE	pBLUP	rel
G1	6.79	6.34	8.59	6.54	5.92	6.05	7.24	5.92	7.91	6.81	6.72	0.67
G2	6.63	7.49	8.71	4.92	7.44	6.48	6.59	7.44	7.64	7.04	6.87	0.67
G3	6.53	7.20	7.82	5.86	6.38	6.09	6.18	6.38	7.14	6.62	6.59	0.67
G4	6.67	6.57	7.12	6.33	6.62	5.64	6.23	6.62	8.43	6.69	6.64	0.67
G5	5.30	6.55	6.19	7.03	7.66	5.26	5.93	7.66	7.21	6.53	6.53	0.67
G6	5.60	6.65	5.44	5.73	5.30	4.88	7.39	5.30	7.70	6.00	6.17	0.67
G7	5.87	6.49	7.22	6.45	5.96	5.49	6.24	5.96	6.44	6.24	6.33	0.67
G8	6.17	6.13	7.35	5.45	5.53	6.76	6.76	5.53	7.99	6.41	6.45	0.67
G9	5.85	6.70	6.32	6.54	5.82	6.06	7.03	5.82	6.96	6.34	6.40	0.67
G10	6.58	5.87	8.08	5.77	7.25	6.76	6.54	7.25	7.14	6.80	6.71	0.67
G11	5.76	6.26	7.41	6.62	5.92	5.91	6.59	5.92	7.22	6.40	6.44	0.67
G12	6.19	6.98	7.00	6.79	5.66	5.04	6.39	5.66	6.09	6.20	6.31	0.67
G13	6.19	6.23	6.86	5.44	6.35	7.12	6.80	6.35	7.96	6.59	6.57	0.67
G14	4.56	5.92	6.63	6.05	5.91	4.66	5.90	5.91	6.24	5.75	6.01	0.67
G15	6.75	6.59	7.43	6.65	7.78	6.24	6.86	7.78	7.65	7.12	6.91	0.67
G16	5.87	6.35	6.51	6.48	6.78	6.41	6.38	6.78	7.19	6.48	6.50	0.67
G17	5.63	6.75	7.46	6.06	5.71	7.18	6.81	5.71	8.33	6.49	6.51	0.67
Avg	**6.06**	**6.53**	**7.19**	**6.16**	**6.35**	**6.00**	**6.58**	**6.35**	**7.37**	**6.50**	**6.51**	
h2b	0.91	0.34	0.91	0.67	0.61	0.85	0.30	0.61	0.82	0.19		
SE	0.12	0.29	0.23	0.23	0.48	0.28	0.32	0.48	0.19	0.26		
LSD	0.24	0.57	0.45	0.45	0.94	0.55	0.63	0.94	0.37	0.51		

*** Genotypes (GEN), Pooled Best Linear Unbiased Estimation (pBLUE), Pooled Best Linear Unbiased Prediction (pBLUP), reliability (rel), Average (Avg), Heritability (h2b), standard error (SE), Least Significance difference (LSD).
Satkhira (E1), Sonagazi (E2), Bhanga (E3), Cumilla (E4), Gazipur (E5), Habiganj (E6), Kushtia (E7), Rajshahi (E8), Rangpur (E9)

3.2. Inter-location correlation patterns across nine test environments

The correlation analysis of grain yield across the nine tested locations indicated substantial variability in inter-location associations (Fig. 2). Several location pairs showed substantial positive association ($p < 0.05–0.001$), indicating similarities in genotype in the case of yield performance under comparable environmental conditions. Notably, Habiganj exhibited strong positive associations with Rangpur ($r = 0.57$, $p < 0.001$), Satkhira ($r = 0.52$, $p < 0.01$), and Bhanga ($r = 0.43$, $p < 0.05$). In addition, Rajshahi was positively correlated with Satkhira ($r = 0.52$, $p < 0.01$), while Satkhira displayed high correlations with both Bhanga ($r = 0.59$, $p < 0.001$) and Rangpur ($r = 0.47$, $p < 0.01$). In contrast, certain pairs, such as Kushtia–Habiganj ($r = 0.10$) and Cumilla–Rajshahi ($r = –0.31$), exhibited weak or negative associations, indicating significant environmental diversity with distinct genotype-by-environment responses.

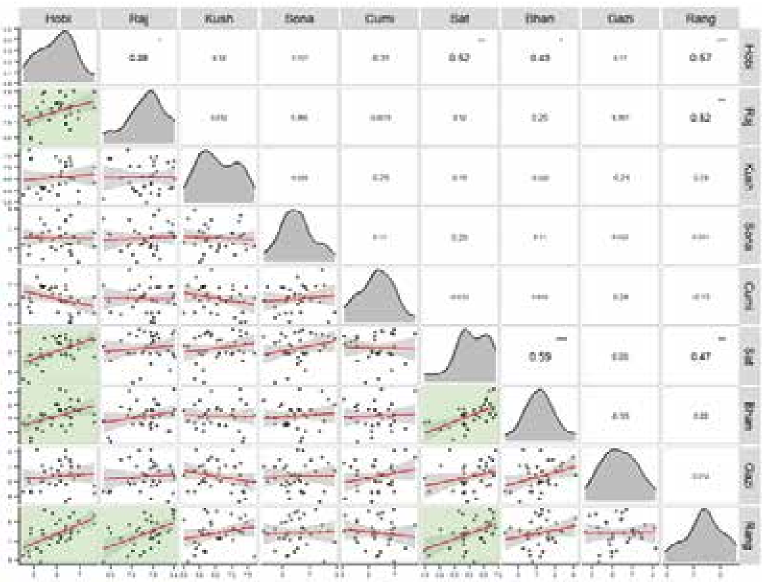

Fig. 2. Pairwise correlation matrix of grain yield across nine test locations (Habiganj, Rajshai, Kushtia, Sonagazi, Cumilla, Satkhira, Bhanga, Gazipur, and Rangpur). Diagonal panels show density plots, upper panels display correlation coefficients with significance levels * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$), and lower panels present scatter plots with fitted regression lines.

Growth duration (GD) demonstrated a positive relationship ($p < 0.05$-0.001) across every location pair (Fig. 3), illustrating similar maturity trends among genotypes in different environments.

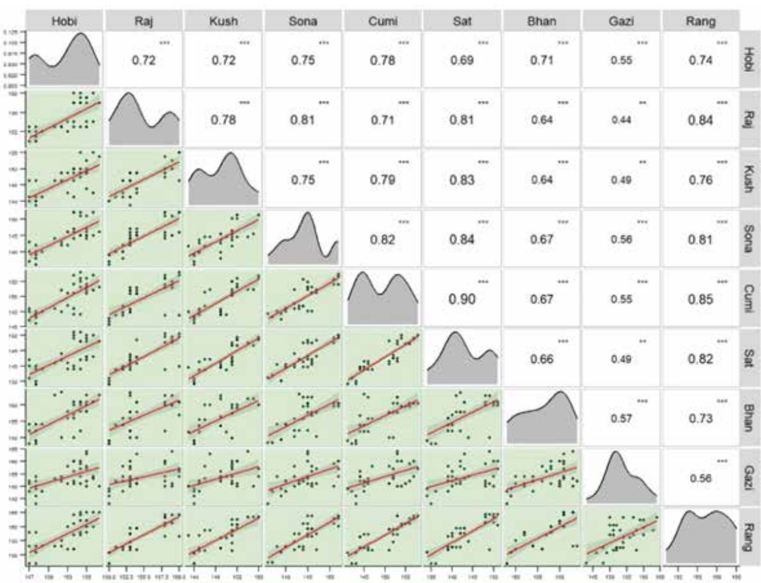

Fig. 3. Pairwise correlation matrix of rice growth duration (days) across nine test locations (Habiganj, Rajshai, Kushtia, Sonagazi, Cumilla, Satkhira, Bhanga, Gazipur, and Rangpur). Diagonal panels show density plots, upper panels display correlation coefficients with significance levels * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$), and lower panels present scatter plots with fitted regression lines.

In addition, plant height (PH) revealed substantial positive associations across the locations ($p < 0.05$-0.001) (Figure 4), indicating uniformity in plant stature under different climatic conditions. Cumilla was an exception, with four non-significant relationships with Habiganj, Kushtia, Bhanga, and Gazipur, demonstrating that plant height expression is influenced by environmental factors of this location.

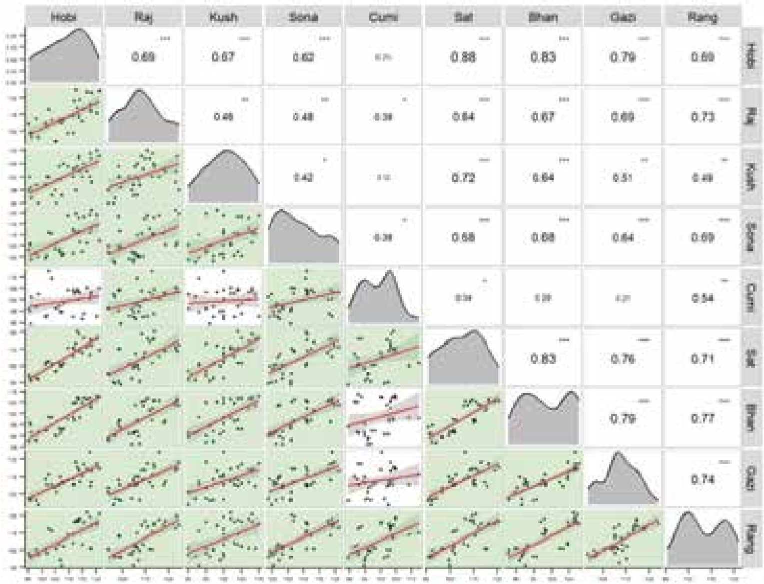

Fig. 4. Pairwise correlation matrix of plant height (cm) across nine test locations (Habiganj, Rajshai, Kushtia, Sonagazi, Cumilla, Satkhira, Bhanga, Gazipur, and Rangpur). Diagonal panels show density plots, upper panels display correlation coefficients with significance levels * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$) and lower panels present scatter plots with fitted regression lines.

3.3. PCA-based assessment of genotype performance across diverse rice-growing environments

The PCA biplot (Fig. 5) shows the connections between 17 rice genotypes (G1-G17) and three traits viz. grain yield, growth duration, and plant height. The first two principal components, PC1 and PC2, explained 47.1% and 37.9% of total variation, respectively, and accounted for a total of 85.0% of the observed variance. PC1 was robustly and positively linked to grain yield and growth duration, as seen by their vectors near alignment, whereas PC2 was primarily connected with plant height. Genotypes positioned near specific traits on the biplot indicate higher performance for those traits. For example, G1 and G2 were near the YLD vector, indicating better yield performance, whereas G4, G13, and G17 were closer to the GD vector, indicating a longer maturity period. G11 and G12 were situated closer to the PH vector, indicating higher plant height.

The genotypes (e.g., G9, G15) close to the origin performed averagely for the examined characteristics, whereas those (e.g., G7, G16) placed in opposite directions from the trait (YLD) vector likely performed worse. The large dispersion of genotypes across all quadrants indicates significant variation in trait combinations, implying that the examined lines exhibit a variety of adaptation strategies (Fig. 5).

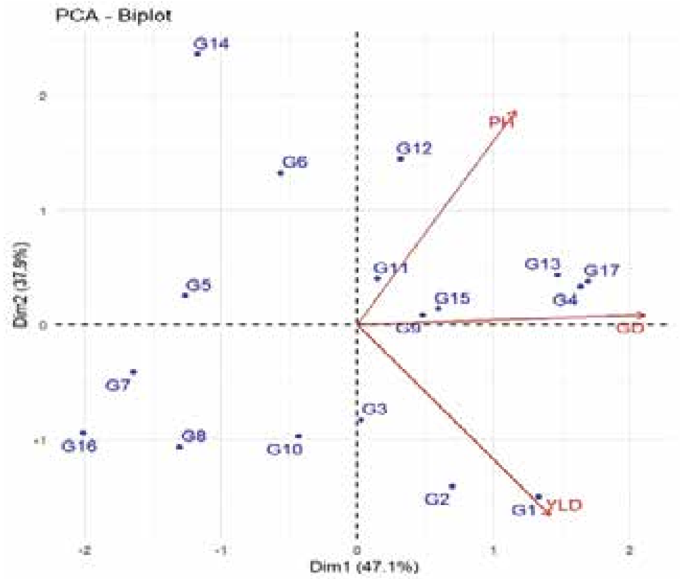

Fig. 5. Principal component analysis (PCA) biplot showing the relationship among 17 rice genotypes (G1–G17) and three traits—grain yield (YLD), growth duration (GD), and plant height (PH)—across environments.

3.4. Environmental evaluation and grain yield adaptability of the genotypes in specific environments

Evaluation of discriminativeness vs. representativeness was performed using GGE bi-plots. The biplot (Fig. 6) demonstrated that PC1 and PC2 explained 42.39% and 20.63% of the total variation, respectively. Environments E6, E9, E3, and E5 were the most discriminative, whereas E3 was also being highly representative of the target environment (Fig. 6). E4 and E1 had moderate discriminative ability, but E4 showed low representativeness, while E8 and E2 were the least discriminative. Genotypes G8, G13, and G17 were closely associated with E6 and E9, suggesting broad adaptation, whereas G2 and G5 showed possible specific adaptation to E5 and E4, respectively.

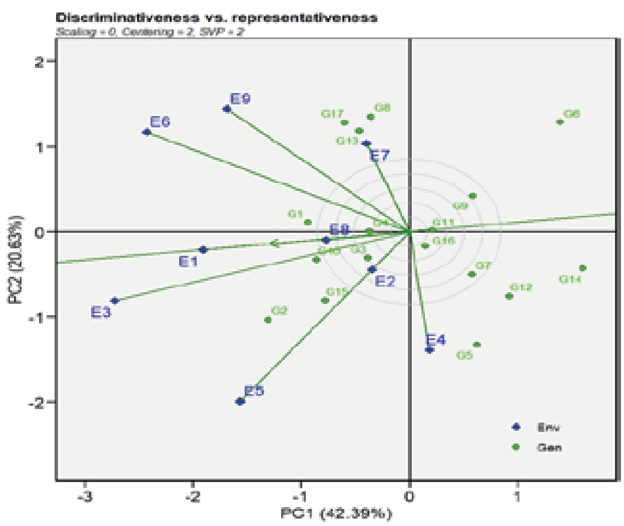

Fig. 6. Discriminativeness and representativeness GGE biplot for Evaluation of Environment.

Mega-environments have been identified employing the "which-won-where" pattern from the GGE biplot (Fig. 7). Perpendicular lines connecting the biplot origin to the polygon's sides split the environments into distinct sectors. The first mega environment (ME) included E6, E9, and E7 genotypes, with G7 and G8 dominating the others. The second ME contained E1, E2, E3, E5, and E8, with G2 the winner. The third ME was made up only of E4, with G5 and G14 emerging as the best-performing line.

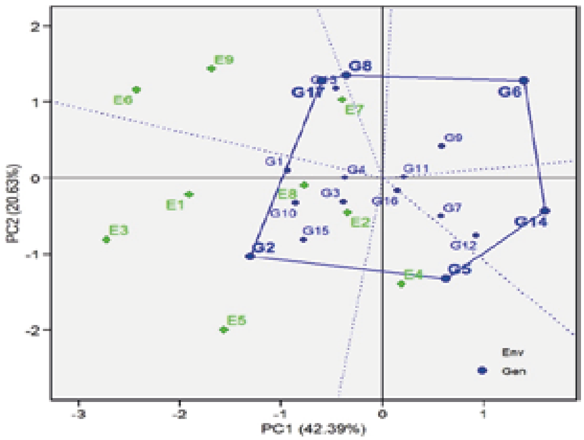

Fig. 7. GGE Biplot Showing "Which-Won-Where" Pattern of Rice Genotypes Across Test Environments for identification of Mega-Environment (ME) and location specific winning genotype.

3.5. Genotypic performance and stability based on gge biplot analysis

The genotypic performance and stability were analyzed using GGE biplot analysis from two perspectives: "Ranking Genotypes" and "Mean vs. Stability" as shown in the Figures 8 and 9, respectively. Both biplots had been generated using scaling = 0, centering = 2, and SVP = 2.

In the "Ranking Genotypes" biplot (Fig. 8), genotypes were ranked according to their proximity to the "ideal genotypes" defined as the genotype with the highest mean performance and the greatest stability. The genotypes G2, G15, G1, and G10 were closest to the optimal genotype position, indicating higher performance across contexts. The genotypes notably G6 and G14 were far from the AEC axis, implying poor performance.

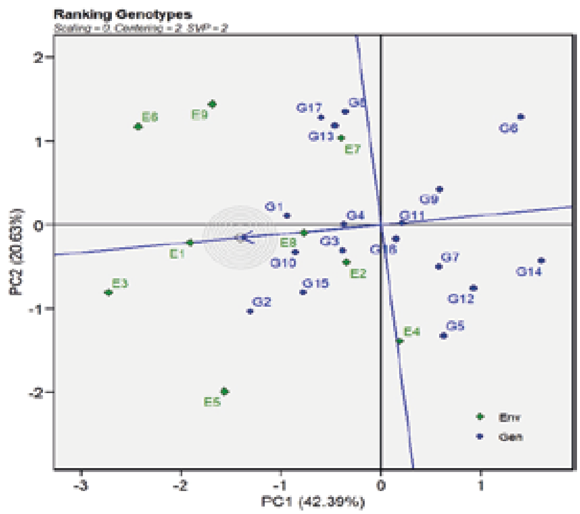

Fig. 8. GGE Biplot Ranking of Rice Genotypes for Mean Yield and Stability across Environments.

The "Mean vs. Stability" biplot (Fig. 9) offered additional details by extracting genotypic performance and stability. The genotypes G2, G15, G1, and G10 were found around the AEC abscissa, indicating higher average performance; however, only G1 and G10 had extremely short projections onto the coordinate, showing high mean performance and stability. G3 and G4 performed similarly to the mean, with very good stability, owing to their short expansions from the AEC coordinate. Overall, these analyses proved G1 and G10 as the most preferable genotypes, integrating high yield performance with greater stability, making them an excellent choice for selection in breeding programs aimed at broad adaptation. Other genotypes, such as G2, G3, G4, and G15, had a favorable profile that warranted additional investigation.

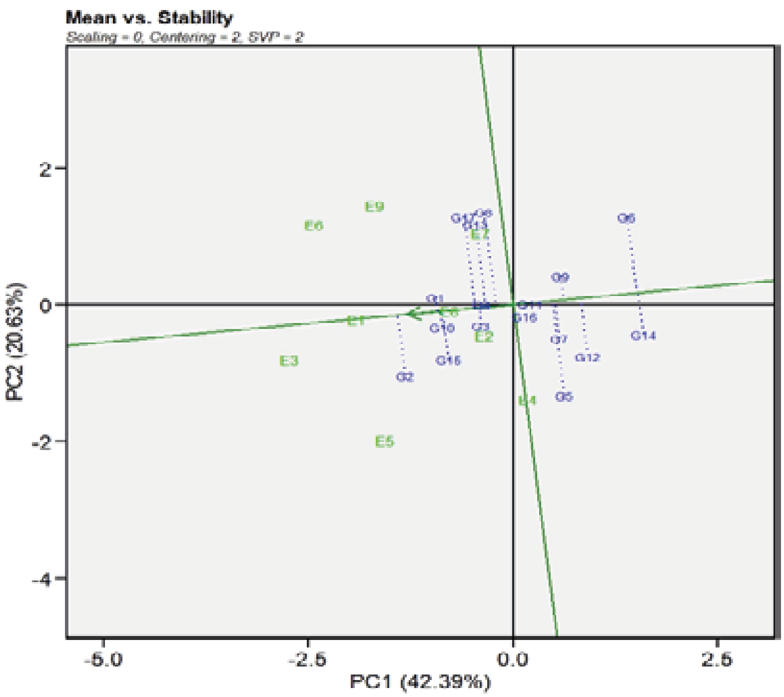

Fig. 9. Mean vs. Stability Biplot Depicting Genotypic Performance across Multi-Environment Trials.

3.6. Multi-trait selection and stability assessment using MGIDI

The Multi-trait Genotype-Ideotype Distance Index (MGIDI) approach was used to find superior genotypes based on various variables (yield, plant height, and growth duration) while taking into account both performance and stability. The first panel (left) exhibits the multi-trait stability index, which ranks genotypes according to their MGIDI scores (Fig. 10). A lower MGIDI number suggests greater proximity to the ideotype, and thus better performance across attributes. Based on a specified selection criterion (horizontal line), seven genotypes-G1, G8, G16, G15, G4, G7, and G11 were recognized as selected (highlighted in blue), while the others were classed as non-selected (red). The second panel (center) shows the impact of each genotype to the MGIDI index, proving that selected genotypes consistently have shorter distances to the ideotype, indicating greater multi-trait performance (Fig. 10). Among the genotypes, G1, G17, and G4 had the lowest MGIDI scores, indicating that they are the most promising candidates for advancement. The third panel (right) shows the strengths and weaknesses view, with the top-performing genotype G1 alongside G4 and G17 for comparison reasons. The polygon depicts each genotype's proportionate contribution to the main factor (FA1), with G1, G4, and G17 having a well-balanced and narrow polygon shape, indicating more consistent performance across traits and fewer deficiencies (Fig. 10). Overall, the MGIDI analysis effectively integrated multi-trait information, allowing for the selection of genotypes with superior and stable performance profiles such as G1, G17, and G4, resulting in more informed selection decisions in breeding programs.

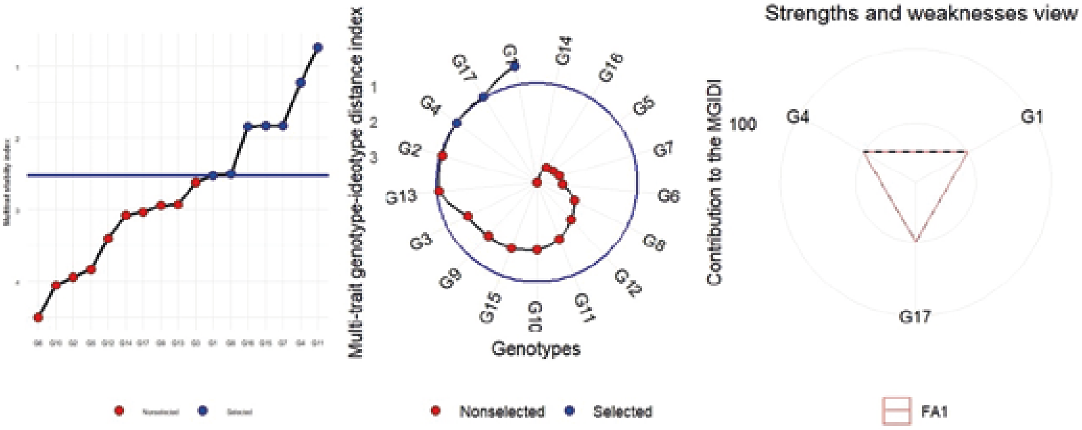

Fig. 10. Multi-Trait Genotype-Ideotype Distance Index (MGIDI) Analysis Showing Genotype Selection, Contribution to Ideotype, and Strengths-Weaknesses Profile.

3.7. Grain quality assessment of rice genotype

To access the grain quality, seventeen rice genotypes were tested for milling quality, grain physicochemical parameters, and cooking properties (Table 5). Milling outturn (%MOT) was attractive in all entries, above the desired criterion of 60%, ranging from 66.9% in G1 (BR11866-5R-277) to 73.0% in G5. Head rice recovery (%HRR) denotes post-milling grain integrity and should be greater than 50% to meet market standards. G3 obtained the highest %HRR (70.0%), followed by G17 (61.7%), G4 (61%), G1 (57.7%), and G10 (57.5%). On the contrary, G11 obtained the lowest %HRR (20.9%).

Grain length and breadth express the significant variation among the genotype which varies from 5.5 mm (G14) to 6.6 mm (G2) and 1.9 mm (G6, G12, G14) to 2.5 mm for grain length and breadth, respectively. The tested genotypes were classed into three groups based on grain size and shape (S&S), i.e., six genotypes long-bold (LB), nine medium-bold (MB), and two long-slender (LS). The alkali spreading value (ASV) denotes the gelatinization temperature, which ranges from 3.1 (G14) to 7.0 (G2, G11). Amylose content (%A) measures the stickiness or non-stickiness of cooked rice, which should be greater than or equal to 24% to meet the national preference of Bangladesh. Amylose content (%A) of tested genotypes ranges from 16.8% (G14), and 27.5% (G17), and thirteen out of seventeen genotypes fulfill the amylose content criteria. Protein content added nutritional value to rice, which spanned from 7.5% (G17) to 10.5% (G14) in the tested genotypes. Cooking time is another quality property as the short of the cooking time, the greater the ability to save national energy which varies between 12.3 min (G12) and 19.3 min (G17). The elongation ratio denoted the length expansion after cooking, which ranges from 1.3 to 2.4, and G7 (BR12125-6R-6) displaying the most expansion during cooking. Imbibition ratio (IB) measures water absorption during cooking, which ranging from 2.6 (G2) to 4.5 (G7, G16) in the tested genotypes.

Overall, genotypes G1, G2, G4, G5, G10, G13, G15, G16, and G17 demonstrated adequate quality parameters at the national preference criterion, making them promising candidates for varietal release and breeding. On the other hand, G3, and G14, despite of good milling output and head rice recovery, were rejected from selection because their amylose content was below the desired range.

Table 5

Grain quality parameters of 17 rice genotypes evaluated for milling, cooking, and physicochemical traits.

GEN	%MOT	%HRR	L	B	S&S	ASV	%A	%P	CT	ER	IB
G1	66.9	57.7	6.2	2.5	LB	3.2	26	8.3	16.3	1.3	2.7
G2	69.7	51.5	6.6	2.4	LB	7	25	8	14.3	1.3	2.6
G3	70	51.6	5.9	2.5	MB	5	20.9	9	18	1.4	4.1
G4	70.6	61.0	5.9	2.5	MB	3.6	25.6	7.9	17	1.4	3.4
G5	73	53.6	6.4	2.5	LB	3.4	26.2	9.2	18	1.4	3.7
G6	71.8	38	6.2	1.9	LB	4.4	24	9.4	14.30	1.5	3.2
G7	69.5	51.6	6.3	2.1	LB	4.7	23.1	8.9	15.30	2.4	4.5
G8	70	51.5	5.8	2.2	MB	4.4	24	9.4	14.30	1.5	3.2
G9	68.9	47.6	6.1	2.4	LB	3.8	17.7	8.2	14.30	1.3	4
G10	68.6	57.5	6	2.4	MB	4.6	25.7	7.7	13.30	1.4	4.3
G11	69.9	20.9	5.9	2.5	MB	7	25.7	8.8	13	1.4	4.3
G12	70.6	22.5	6.2	1.9	LS	6	26.3	8.6	12.30	1.6	4.3
G13	71.1	70	5.6	2.1	MB	4.2	25.1	8.5	13	1.3	3.3
G14	67.4	61.7	5.5	1.9	MB	3.1	16.8	10.5	13.30	1.3	3.5
G15	69	55.8	6.5	2.3	LB	3.9	26.8	9.8	16.30	1.4	4.3
G16	71.2	59.7	6.2	2	LS	4.8	26	9.8	17.3	1.3	4.5
G17	70	61.7	5.7	2	MB	4.3	27.5	7.5	19.3	1.4	3.5

Here, Milling out-turn (%MOT), head rice recovery (%HRR), Grain length in milli-meter (L), Grain breadth in milli-meter (B), size and shape (S&S), Alkali spreading value (ASV), Amylose content in percentage (%A), Protein content in percentage (%P), cooking time in minutes (CT), Elongation ratio (ER), Imbibition ratio (IB).

3.8. Genomic trait value evaluation by SNP based trait genotyping and screening for bacterial blight and rice leaf blast

Molecular markers were utilized to evaluate the presence of key resistance and quality-related genes across 17 rice genotypes (Table 6). All the tested genotypes carried the *Wax-A* gene, which suggests a link between higher amylose production and maintaining desirable grain quality for national preferences. Twelve among the tested genotypes contained one or more disease resistance genes, that mean more than 70% population already have different levels of resistance against major diseases. Five tested lines have one or more bacterial blight resistance genes i.e., *Xa21, Xa4* and *Xa7*, that's about one-third of the tested population. Notably, G2 had *Xa21* in combination with *BADH2* genes. Besides, nine tested genotypes had one or more blast resistance genes (*Pi9, Pb1, pita*), which represented more than 50% population. Additionally, two (G11 & G12) among the nine blast resistant genotypes had three major blast resistance genes i.e. *Pi9, Pb1, pita*. The heat tolerance-associated QTL *qHTSF4.1* was identified in G7 and G8. The trait marker *TSV1* which is responsible for tungro resistance, was found in G4 and G13. The screening result demonstrated different level of reactions against BB and blast in artificial inoculation (Table 6). Among the genotypes G1, G3, G15 showed resistant (R) and G4 showed moderately resistant (MR) reaction for Bacterial blight. On the other side, genotypes G11, G12 showed resistant (R) and G2, G3, G7, G8, G15 demonstrated moderately resistant reaction against leaf blast. The genotypes G3 and G15 showed moderately resistant to resistant reaction against both BB and blast pathogen. In summary, different combinations of pyramided lines were generated along with good yield potential and grain quality, which will be used as potential donors for improving resilience against major diseases like bacterial blight, blast and tungro.

Table 6

Screening for Bacterial blight (BB) and Leaf blast along with gene composition in seventeen rice genotypes.

GEN	Lesion length (cm)		BB scoring (0-9)	Remarks	Blast Scoring (0-9)			Remarks	Gene (s)
	Iso#1	Iso#2			R1	R2	R3		
G1	1.5	1	1	R	NA	NA	NA	NA	*Wax-A, Xa21, Pb1*
G2	4	5	5	MS	4	4	4	MR	*Wax-A, Xa21, BADH2*
G3	1.5	2	1	R	4	4	3	MR	*Wax-A, Xa21, Pb1*
G4	1	3	3	MR	NA	NA	NA		*Wax-A, tsv1*
G5	5	6	5	MS					*Wax-A, Xa21, Pb1*
G6	NA	NA	NA	NA	4	5	5	MS	*Wax-A*
G7	NA	NA	NA	NA	3	3	3	MR	*Wax-A, Pi9, Pb1, qHTSF4.1*
G8	NA	NA	NA	NA	3	3	4	MR	*Pb1, qHTSF4.1*
G9	NA	NA	NA	NA	NA	NA	NA	NA	*Wax-A*
G10	NA	NA	NA	NA	NA	NA	NA	NA	*Wax-A, Pb1*
G11	NA	NA	NA	NA	0	0	1	R	*Wax-A, Pi9, Pita,Pb1*
G12	NA	NA	NA	NA	1	2	2	R	*Wax-A, Pi9, Pita,Pb1*
G13	NA	NA	NA	NA	5	5	5	MS	*Wax-A, Pb1, TSV1*
G14	NA	NA	NA	NA	5	5	5	MS	*Wax-A*
G15	1	1	1	R	3	3	3	MR	*Wax-A, Xa21, Xa4, Xa7*
G16	20	25	9	HS	NA	NA	NA	NA	*Wax-A*
G17	15	12	9	HS	NA	NA	NA	NA	*Wax-A*

4. Discussion

We tested 17 rice genotypes across nine agro-climatic zones of Bangladesh. The result reveals a significant level of genetic variability with substantial genotype-by-environment (GEI) effect on grain yield and other associated traits. The dominant significant effect of genotype, environment, and GEI demonstrated the importance of cross-environment trials for identifying stable genotypes to maintain across country yield performance. Nowadays most of scientists believe that yield does not rely only on the genotypes but also it is influenced by the environmental heterogeneity like edaphic factors (Mfupe et al., 2023; Huang et al., 2021). The current study demonstrated that the genotypes G1, G2, and G15 performed quite uniformly across all the environments for grain yield. Therefore, the genotypes might be declared as adaptable rice genotypes in case of yield performance (Sandhu et al., 2021). The superior performance of Rangpur and Bhanga suggests these sites provided optimal conditions for expression of yield potential, possibly due to favorable climatic and edaphic factor. To access the inter-location adaptability, the association among the environments was analyzed. The inter-location correlation analysis indicated that certain environments, such as Habiganj and Rangpur, exhibited strong positive associations. The findings suggest similar environmental selection pressures and similar adaptability of rice genotypes. Conversely, weak/poor or negative correlations were demonstrated between the sites like Kushtia–Habiganj and Cumilla–Rajshahi. The findings reflect high environmental divergence, which can be exploited for identifying location-specific adaptation (Habib et al., 2024). The positive correlations were recorded for growth duration and plant height across the most environments which suggested less influence of those traits by environmental variability compared to grain yield.

PCA and GGE biplot analyses further clarified adaptation patterns of the genotypes. The genotypes G1, G2, G15, and G10 exhibited broad adaptability across the environments due to high mean performance and stability. Identified Mega-environments (ME) prove the heterogeneity of the nine agro-climatic zones and also support out breeding strategies. For example, G7 and G8 exhibited broad adaptation to the first ME (E6, E7, and E9), whereas G5 and G14 showed specific adaptation to E4. Such findings emphasize the potential for both wide and location-specific varietal recommendations, in line with the “which-won-where” concept (Ghazy et al., 2023).

As adaptability not only depends on a single trait like yield, though it’s the prime criterion for farmers, and breeders to address the food security. For that’s reason, we conducted a multi-trait stability index and Multi-trait Genotype Ideotype distance index (MGIDI) to select the best adaptable line. In the current study, MGIDI provided a holistic evaluation by integrating yield, growth duration, and plant height performance with stability. The selected genotypes G1, G4, and G17, as closest to the ideotype, indicate their potential for improvement of multiple traits without major complications. This approach enhances selection efficiency by durable productivity with agronomic suitability (Pallavi et al., 2024; Palaniyappan et al., 2024; Al-Mamun et al., 2024).

Stable performance is not enough for a long time adaptation to a variety without attending to the preferences of consumers by maintaining grain quality. That's why grain quality assessment is done to select the best adaptable lines. The results revealed that the most genotypes met or exceeded the national standards of Bangladesh for milling outturn standard (>60%), head rice recovery (>50%), and amylose content (>24%). Genotypes G1, G2, G4, G5, G10, G13, G15, G16, and G17 combined superior milling quality with favorable cooking properties, supporting their dual suitability for market and breeding purposes. Notably, some high-yielding genotypes, such as G3 and G14, were excluded from selection due to suboptimal amylose content, highlighting the need to integrate quality traits into varietal development pipelines.

Nowadays, molecular techniques have become a more reliable approach by discovering high-throughput genotyping for trait selection. The SNP based trait genotyping emerges as a quick and reliable method for different stress breeding like disease resistance. The SNP-based genotyping of current genotypes revealed the successful pyramiding of resistance genes against multiple biotic stresses, including BB (*Xa21, Xa4, Xa7*), blast (*Pi9, Pita, Pb1*), and tungro (*TSV1*), along with heat tolerance QTL (*qHTSF4.1*). The combined effect of those genes improves broad-spectrum durable resistance and reduces reliance on chemicals for disease management (Fiyaz et al., 2022). Screening for BB and blast resistances demonstrate range of reactions against BB and blast which support the genotyping results. From screening and genotyping result, it should be concluded that G2, G3 and G15 might be potential elite parents with multiple resistance genes and higher yield for the bacterial disease resistance breeding program. However, the durability of resistance genes remains a challenge due to pathogen evolution, the need for continuous monitoring, and strategic deployment of R-gene combinations (Michelmore et al., 2013).

Overall, the integration of multi-environment yield evaluation, grain quality assessment, and genomic profiling in this study enabled the selection of both broad and specific adaptation of the selected genotypes. The genotypes G1, G10, G2, G15, G4, and G17 emerged as particularly valuable for breeding programs aiming to develop rice cultivars with stable high yield, desirable quality traits, and durable resistance to major diseases. Furthermore, G1 and G4 genotypes have the potential to be good performing genotypes for bacterial blight resistance. In future these genotypes should be incorporated for line development using genomic selection models to accelerate genetic gain of the breeding programs.

References

Al. Mamun, S. A., Ivy, N. A., Khan, M. A. I., Rehana, S., Sultana, M. S., Adhikary, S. K., & Islam, M. M. (2024). Genotype selection from azide-induced rice mutants using multitrait genotype–ideotype distance index (MGIDI): Unveiling promising variants for yield improvement. Advances in Agriculture, 2024(1), 5719580.

Bunawan, H., Dusik, L., Bunawan, S. N., & Amin, N. M. (2014). Rice tungro disease: From identification to disease control. World Appl. Sci. J, 31(6), 1221-1226.

Debnath, P., Chakma, K., Bhuiyan, M. S. U., Thapa, R., Pan, R., & Akhter, D. (2024). A novel multi trait genotype ideotype distance index (MGIDI) for genotype selection in plant breeding: Application, prospects, and limitations. Crop Design, 3(4), 100074.

Dey, S. R., Das, R., & De, M. (2024). A brief review on present status of rice tungro disease: types of viruses, vectors, occurrence, symptoms, control and resistant rice varieties. Int. J. Adv. Life Sci. Res, 7, 15-23.

Egea-Gilabert, C., Pagnotta, M. A., & Tripodi, P. (2021). Genotype× environment interactions in crop breeding. Agronomy, 11(8), 1644.

Fiyaz, R. A., Shivani, D., Chaithanya, K., Mounika, K., Chiranjeevi, M., Laha, G. S., ... & Sundaram, R. M. (2022). Genetic improvement of rice for bacterial blight resistance: Present status and future prospects. Rice Science, 29(2), 118-132.

Fukagawa, N. K., & Ziska, L. H. (2019). Rice: Importance for global nutrition. Journal of nutritional science and vitaminology, 65(Supplement), S2-S3.

Ghazy, M. I., Abdelrahman, M., El-Agoury, R. Y., El-Hefnawy, T. M., El-Naem, S. A., Daher, E. M., & Rehan, M. (2023). Exploring genetics by environment interactions in some rice genotypes across varied environmental conditions. Plants, 13(1), 74.

Habib, M. A., Azam, M. G., Haque, M. A., Hassan, L., Khatun, M. S., Nayak, S., ... & Sarker, U. (2024). Climate-smart rice (*Oryza sativa* L.) genotypes identification using stability analysis, multi-trait selection index, and genotype-environment interaction at different irrigation regimes with adaptation to universal warming. Scientific Reports, 14(1), 13836.

Halekoh, U., & Højsgaard, S. (2014). A kenward-roger approximation and parametric bootstrap methods for tests in linear mixed models–the R package pbkrtest. Journal of Statistical Software, 59, 1-32.

Huang, X., Jang, S., Kim, B., Piao, Z., Redona, E., & Koh, H. J. (2021). Evaluating genotype× environment interactions of yield traits and adaptability in rice cultivars grown under temperate, subtropical and tropical environments. Agriculture, 11(6), 558.

Iqbal, J., Yousaf, U., Asgher, A., Dilshad, R., Qamar, F. M., Bibi, S., ... & Haroon, M. (2023). Sustainable rice production under biotic and abiotic stress challenges. In Sustainable agriculture in the era of the OMICs revolution (pp. 241-268). Cham: Springer International Publishing.

Justo, S. B., Mkamilo, H. G., Danga, N. O., Huseni, R., Bakari, F. S. A., Mwakapala, R. A., Lee, S. B. et al. (2024). Genotype and genotype x environment interaction effects on the rice grain yield performance in different agro-ecologies in Tanzania.

Kassambara, A., & Mundt, F. (2017). Package factoextra: Extract and visualize the results of multivariate data analyses. R package version 1.0. 7. Foundation for Statistical Computing, Vienna, Austria.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: tests in linear mixed effects models. Journal of statistical software, 82, 1-26.

Latif, M. A., Kayess, O., Hasan, R., & Rahman, L. (2025). Molecular marker assisted gene stacking for multiple diseases resistance in an elite rice cultivar, BRRI dhan48. Plant Gene, 42, 100505.

Lenth, R. (2025). emmeans: Estimated marginal means, aka Least-Squares Means. R package (Version 1.11. 2-00002).

Mendiburu, FD. (2020). Agricolae: Statistical Procedures for Agricultural Research. R Package Version 1.3-3. 2020.

Mfupe, B. P., Msolla, S. N., & Chilagane, L. A. (2023). Genotype and Environment Interaction for yield performance of 12 Advanced Tongil rice genotypes with Doubled Haploid Background under Salts tress conditions in Tanzania. African Journal of Agricultural Research, 19(8), 857-867.

Michelmore, R. W., Christopoulou, M., & Caldwell, K. S. (2013). Impacts of resistance gene genetics, function, and evolution on a durable future. Annual review of phytopathology, 51(1), 291-319.

Olivoto, T., & Lúcio, A. D. C. (2020). metan: An R package for multi-environment trial analysis. Methods in Ecology and Evolution, 11(6), 783-789.

Olivoto, T., Lúcio, A. D., da Silva, J. A., Marchioro, V. S., de Souza, V. Q., & Jost, E. (2019). Mean performance and stability in multi-environment trials I: combining features of AMMI and BLUP techniques. Agronomy journal, 111(6), 2949-2960.

Palaniyappan, S., Arunachalam, P., Banumathy, S., & Muthuramu, S. (2024). Introspection of discriminate function analysis and MGIDI selection index for selection to improve yield in rice (*Oryza sativa* L.). Indian journal of genetics and plant breeding, 84(02), 202-208.

Pallavi, M., Prasad, B. M., Shanthi, P., Reddy, V. L. N., & Kumar, A. N. (2024). Multi trait genotype-ideotype distance index (MGIDI) for early seedling vigour and yield related traits to identify elite lines in rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 15(1), 120-131.

Pedrozo, R., Osakina, A., Huang, Y., Nicolli, C. P., Wang, L., & Jia, Y. (2025). Status on genetic resistance to rice blast disease in the post-genomic era. Plants, 14(5), 807.

Sandhu, N., Yadav, S., Catolos, M., Cruz, M. T. S., & Kumar, A. (2021). Developing climate-resilient, direct-seeded, adapted multiple-stress-tolerant rice applying genomics-assisted breeding. Frontiers in plant science, 12, 637488.

Wang, X., Lee, S., Wang, J., Ma, J., Bianco, T., & Jia, Y. (2014). Current advances on genetic resistance to rice blast disease. Rice-Germplasm, genetics and improvement, 195-217.

Widiarta, I. N., Firmansyah, F., Yunus, M., Apriana, A., Sisharmini, A., Santoso, T. J., ... & Hairmansis, A. (2025). Rice virus disease in Indonesia: epidemiology and varietal resistance. Phytopathology Research, 7(1), 11.

Yan, W., Hunt, L. A., Sheng, Q., & Szlavnics, Z. (2000). Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop science, 40(3), 597-605.

Yan, W., & Kang, M. S. (2002). GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. CRC press.

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Dissecting Genotype x Environment Interaction and Adaptability for Grain Yield in Irrigated Rice Systems

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A R T I C L E I N F O

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A B S T R A C T

Rice cultivation is widely adapted across diverse agro-climatic zones and serves as a global staple food, supplying up to 75% of caloric intake for nearly 3 billion people worldwide. In Bangladesh, evolving climate patterns are increasingly threatening rice productivity across diverse agro-ecological regions. Therefore, identifying stable, high-yielding genotypes across agro-climatic zones in Bangladesh is essential for sustaining national food security. This study evaluated the yield stability of 10 advanced inbred lines with 2 HYV as checks across 10 diverse agro climatic zones using AMMI and GGE models. Eight yield-related traits were analyzed, including days to maturity, plant height, number of effective tillers, panicle length, number of filled grains, percent spikelet sterility, 1000-grain weight, and grain yield. Combined ANOVA revealed significant effects of genotype, environment, and GEI on all traits, which were significantly associated with yield. The first two PCs explained 29.8% and 23.5% of variation in AMMI, and 30.66% and 22.79% in GGE. Among the studied genotypes, we found genotype G6 (NGR750-1) was the most stable comparable to the check HYV BRRI dhan89. Stability analysis showed that GEI strongly affects grain yield and the selection of stable genotypes across environments. Further investigation is required to elucidate the adaptive mechanisms of the identified genotype, focusing on physiological and molecular determinants of grain yield across diverse environments. The identified genotype could be used further within the framework of the rice improvement program or released as a high-yielding cultivar following multi-location evaluation.

1. Introduction

Rice (*Oryza sativa* L.) is a cereal crop of global significance, and as a major food source, it provides 35-75% of the calories consumed by over 3 billion people worldwide (Yu et al., 2012; Biswas et al., 2024). Global annual rice production exceeds 800 million metric tons, with cultivation spanning approximately 160 million hectares worldwide (FAOSTAT, 2024). It is grown under a variety of agro climatic conditions. Plant breeders frequently use yield performance and phenotypic expression to screen and select rice cultivars in test environments. Their efforts are more effective and successful as a result of these methods, to

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the point where their decisions provide a complete understanding of the environmental influences on the associated mechanisms and the phenotypic expression of such influences. As a result, the majority of crop technology efforts are focused on reducing risk, increasing yield stability, lowering costs, and increasing high returns (Oladosu et al., 2016). The rapid growth of world population, climate change, and limited arable land are expected to increase the production of cereal crops such as rice, wheat, and maize (Kang and Priyadarshan, 2007; Cordero-Lara, 2020). Rice production and productivity are hampered by a variety of factors, including a lack of improved varieties, diseases, and pre-and post-harvest machinery (MoARD, 2010).

In Bangladesh, rice is the staple food crop and plays a central role in food security and the national economy. The enormous area of over 11.46 million hectares helps Bangladesh to produce about 40.46 million tons of rice, placing the country as the third largest rice-producing in the world (BBS, 2025; FAOSTAT, 2025). The average yield of clean rice is just 3.55 tha-1, which is significantly less than the potential yield of the widely used cultivated rice varieties. The main cause of the lower average yield is the variety's poor performance in various environments. New cultivars with high production potential and broader adaptability should be developed to cope with the continuously growing population. Yield is a complex trait that is largely influenced by genetic and environmental factors. It also depends on numerous traits. An ideal crop genotype should have a high mean yield and yield stability when grown in a diverse environment. Plant breeding programs and the introduction of new crop cultivars depend on the G X E interactions (McLaren and Chaudhary, 1994; Prasad and Singh, 1990).

The interaction between genotype and environment is a major concern of breeders. A genotype's stability performance is a trait that is genetically impacted (Patra and Mohanty, 1987). Wider adaptability and stability are crucial for developing an efficient breeding program. Determining a genotype's performance in various environments requires examining G × E interactions. This experiment examined certain progressive breeding lines and varieties as checks across various environments to identify the best and most stable genotypes.

The Additive Main Effects and Multiplicative Interaction (AMMI) model is a hybrid model that separates the additive variance from the interaction portion and then uses Principal Component Analysis (PCA) to generate a new set of coordinate axes that better explains the interaction pattern (Islam et al., 2014; Khatun et al., 2026). The AMMI analysis and the biplot facility were used to analyze the promising rice yield data in order to identify high yielding and stable genotypes that are adapted to various production environments, to determine the nature and size of G x E interaction effects on grain yield in diverse production environments, and to identify the regions where rice genotypes would be adapted and produce competitive yields on a cost-benefit basis.

The study aimed to analyze the promising rice yield data in order to identify high yielding and stable genotypes that are adapted to various production environments. It also aimed to ascertain the nature and size of G x E interaction effects on grain productivity under diverse agro-climatic conditions and to pinpoint the regions where rice genotypes would be adapted and produce competitive yields based on a cost-benefit analysis.

2. Materials and method

2.1. Study area, Plant materials, Experimental design and Procedures

The study was carried out at nine BRRI regional stations and the headquarter of BRRI, viz., Barishal (E1), Rangpur (E2), Gazipur (E3), Bhanga (E4), Cumilla (E5), Gopalganj (E6), Habiganj (E7), Kushtia (E8), Rajshahi (E9), and Sonagazi (E10) of Bangladesh during the Boro season 2021-22. The trials were carried out under irrigated conditions. The study included ten rice genotypes, including two standard checks, viz., NGR 414-1(G1), NGR 418-1(G2), NGR 467-2(G3), NGR 521-2(G4), NGR 522-1(G5), NGR 750-1(G6), NGR 796-2(G7), NGR 1161-3(G8), NGR 1255-1(G9), NGR 1308-2(G10), BRRI dhan58 (G11), and BRRI dhan89 (G12).The experiment was set up at each location using a randomized complete block design with three replications. Thirty-five-days-old seedlings were planted at 2-3 seedlings with a spacing of 20 cm x 20 cm. The unit plot size was 10.8 m2. Inorganic fertilizers were applied @ 260:100:120: 110:10 kg urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum and zinc sulphate per hectare, respectively. Urea was applied in three equal splits at 15 days interval starting from 12 days after transplanting. Total amount of TSP, two-thirds of MoP, gypsum and zinc sulphate were applied at final land preparation. Rest one-third of MoP was applied with the third top dressing of urea. Crop management practices were done as and when necessary.

2.2. Site Characterization and Weather Condition

A panel of twelve advanced rice lines was cultivated in 10 different environments covering 9 out of 30 agro ecological zones determined on the basis of physiographic, hydrology, cropping pattern, season, soil types, and tidal activity of Bangladesh. The range of the average temperature during the cropping period (Nov. to May) was 22.55 to 26.130C. The highest degree of average temperature was observed in Cumilla, followed by Sonagazi (24.560C), Gazipur (24.480C) and Barishal (24.080C), and the average temperature found in Rangpur. The highest average relative humidity prevailed in Barishal (80.83%), whereas the lowest average was found in Rangpur (67.79%). During the cultivated period, the average precipitation rate ranged from 4.99 mm in Habiganj followed by Cumilla (2.82 mm), Sonagazi (2.61 mm), and Rangpur (2.15 mm) to 0.48 mm in Rajshahi. The highest average sunshine period was recorded in Kushtia (6.93 hrday-1) and the lowest average was calculated in Rangpur (5.01 $hrday^{-1}$).

2.3. Data collection

Five representative plants for each genotype in each replication were randomly selected to record data on eight different yield and yield contributing traits such as days to maturity (days), plant height (cm), effective tillers per hill (no.), panicle length (cm), filled grains per panicle (no.), spikelet sterility (%), 1000-grain weight (g), and grain yield (tha^{-1}).

2.4. Data analysis

The aggregated information from different environments was used to perform an analysis of variance (ANOVA), boxplots of yield and yield component traits, GGE biplots for discrimination and representativeness, GGE biplots (which-won-where pattern), and Multi-trait Stability Index (MTSI) analysis using an R package for multi-environment trial analysis (Olivoto and Lúcio, 2020).

3. Results and discussions

3.1. Yield and yield contributing traits

The boxplot revealed significant variability in yield-related traits such as plant height, effective tillers, filled grains, and grain yield across 12 genotypes and 10 environments. Average GY was significantly higher in E4 (Bhanga) than in other environments, whereas average plant height (PH), effective tillers per hill (ET), and filled grains per panicle (FG) were higher in E8 (Kushtia), E1 (Barishal), and E6 (Gopalganj) environments, respectively (Fig. 1).

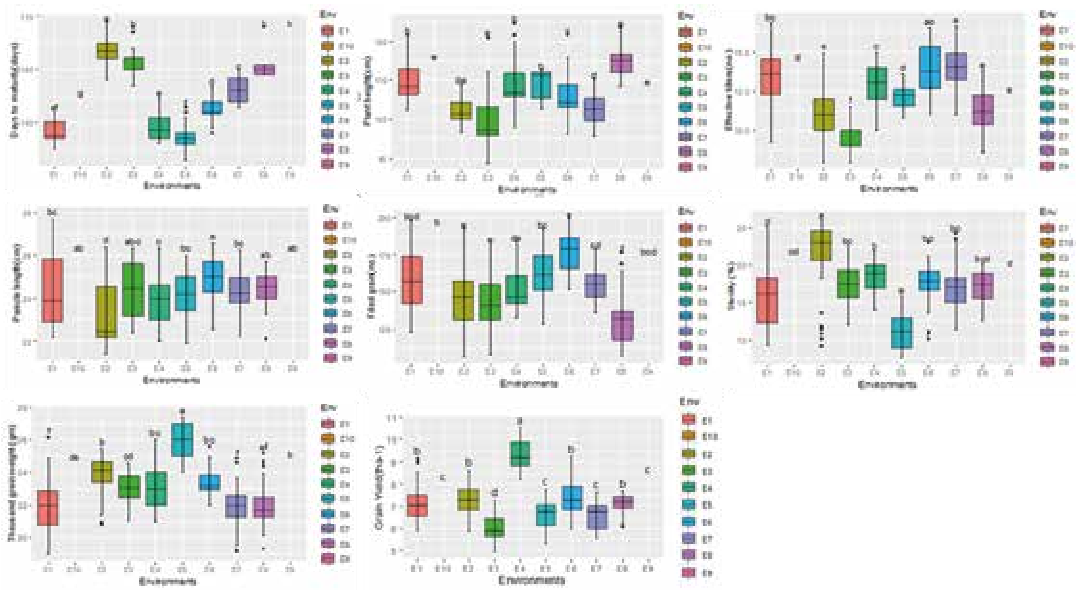

Fig. 1. Comparisons of yield-component traits and grain yield performance among ten environments. Boxplots with different lowercase letters indicate statistically significant differences (One-way analysis of variance followed by Scheffe's post hoc test; $P<0.05$)

To quantify the interactions and describe the main effect among and within the sources of variations, a combined analysis of variance is used. Table 1 indicates the pooled analysis of variance. Days to maturity (days), plant height (cm), effective tillers per hill (no.), panicle length (cm), filled grain per panicle (no.), spikelet sterility (%), thousand-grain weight (g), and grain yield (tha^{-1}) all showed significant differences ($P<0.01$, 0.05). The percentage of variation for all traits is explained by the partitioning of the total sum of squares shown in Table 1. All traits showed significant variation due to environmental factors ranging from 9% to 77%. The majority of the variation in genotype performance is caused by a large difference in genotype mean between locations. In comparison, replication showed the least variation, ranging from 0.33% to 3.46%. Panicle length contributed the most to genotype effects (48.89%), while plant height and spikelet sterility percent showed similar variation due to genotype effects (16.88% and 15.97% of the total sum of squares, respectively). However, there was a small variation due to genotype effect in filled grain number per panicle and grain yield tons per hectare (4.96% and 4.33% of total sum of square, respectively). The total sum of squares for days to maturity, plant height in cm, effective tiller number, panicle length in cm, filled grain number per panicle, spikelet sterility percent, thousand grain weight in g, and grain yield tons per hectare accounted for 7.30%, 16.82%, 15.37%, 19.04%, 26.04%, 20.61%, 14.04%, and 21.92% of the total sum of squares. For days to maturity, the variation in environment (76.63%) indicated that the tested environments in this current study were diverse, with the greatest differences among environment effects causing the most variation in grain yields. The GE interaction explained 21.92% of the variation in yield tons per hectare. For the explained sum of squares of yield tons per hectare, the magnitude of the GE interaction was approximately five times that of genotypic variation. This demonstrated that genotype responses differed significantly across environments. According to Kang and Pham (1991), a large amount of GE interaction reduces genotype effectiveness by confounding yield performance through the dissociation of phenotypic from genotypic value. The substantial degree of variance seen in this study's GE interactions concerning the G impact raised the prospect of various mega-environments with various genotypes that produce high yields (Yan and Kang, 2002). According to Freeman (1973), the main reason for genotype evaluation across a wide range of environments is to estimate adaptability and stability. The significant GE interaction effects demonstrated that genotypes responded differently to different environments or locations, emphasizing the importance of testing rice varieties at multiple locations. It also demonstrates the difficulties that rice breeders face when selecting the best varieties for release. When genotype-by-environment interaction is caused by predictable factor (environment) variation, rice breeders have the option of developing genotypes that perform well in multiple environments (Dehghani et al., 2006). The percentage of explained sum of squares values revealed that the highest proportion of DM variation (76.73%) was due to environment; the highest proportion of PH variation (41.09%); the highest proportion of ET variation (46.43%); the highest proportion of FG variation (26.83%) was due to environment; the highest proportion of ST variation (30.31%) was due to environment; and the highest proportion of TGW variation was due to environment. Genotype effects explained a large proportion of PL variation (48.89%). GY was more affected by the environment and GEI, accounting for 47.55% and 21.92% of total variation, respectively.

Table 1

Combined analysis of variance (ANOVA) of yield-component traits and grain yield.

Source	Df	DM		PH		ET		PL		FG		ST		TGW		GY	
		MS	%ESS	MS	%ESS	MS	%ESS	MS	%ESS	MS	%ESS	MS	%ESS	MS	%ESS	MS	%ESS
E	9	1729.78**	76.63	994.11**	41.09	76.87**	46.43	6.67**	8.97	5743.43**	26.83	226.04**	30.31	51.25**	42.27	29.05**	47.55
Rep (E)	20	5.31*	0.52	19.89**	1.83	2.58**	3.46	0.15NS	0.44	215.31*	2.24	9.35**	2.79	0.41NS	0.76	0.09NS	0.33
G	11	141.89*	7.68	334.12**	16.88	7.17**	5.30	29.76**	48.89	868.58**	4.96	97.43**	15.97	14.10**	14.22	2.17**	4.34
GEI	99	14.98**	7.30	36.99**	16.82	2.31**	15.37	1.29**	19.04	506.77**	26.04	13.98**	20.61	1.55**	14.04	1.22**	21.92
Residuals	220	0.52	0.56	6.48	6.55	0.95	14.07	0.11	3.62	121.67	13.89	2.96	9.71	0.73	14.67	0.10	3.93

E, environment; Rep (E), replication (environment); G, genotype; GEI, genotype-environment interaction; DM, days to maturity in days; PH, plant height in cm; ET, effective tillers number per hill; PL, panicle length in cm; FG, filled grain number per panicle; ST, spikelet sterility percent; TGW, thousand-grain weight in g; GY, grain yield ton per hectare; Df, degrees of freedom; MS, mean square; ESS (%), proportion of explained sum of squares; *, $p < 0.05$; **, $p < 0.01$; ns, not significant.

3.2. Environmental evaluation and adaptability in specific environments

View of GGE biplot (Discrimination and representativeness)

GGE biplots were used to compare discriminativeness and representativeness (Fig. 2). The lengths of environment vectors from the biplot origin are proportional to the standard deviation within each environment, representing the environments' discriminating ability. Among the ten environments, environmental conditions (E1) demonstrated the greatest discriminating ability for ET and PL, while environmental conditions (E2) demonstrated the greatest discriminating ability for FG, ST, and TGW and environmental conditions (E10) demonstrated the greatest discriminating ability for DM and PH. (Fig. 2). Discriminating ability was ranked as follows for the term GY: E9 > E1 > E2 > E3 > E7 > E4 > E5 > E10 > E6 > E8. The angle formed by the environment line and the average environment axis (AEA), which runs through the average environments and biplot origin, indicates how representative each environment is. E2 was more representative than the other environments for DM, ST, and TGW, exhibiting a smaller angle with the AEA line. E7 was the most representative of ET and GY. Environmental condition E1 was the most representative for PH; E9 was the most representative for PL; and E4 was the most representative for FG.

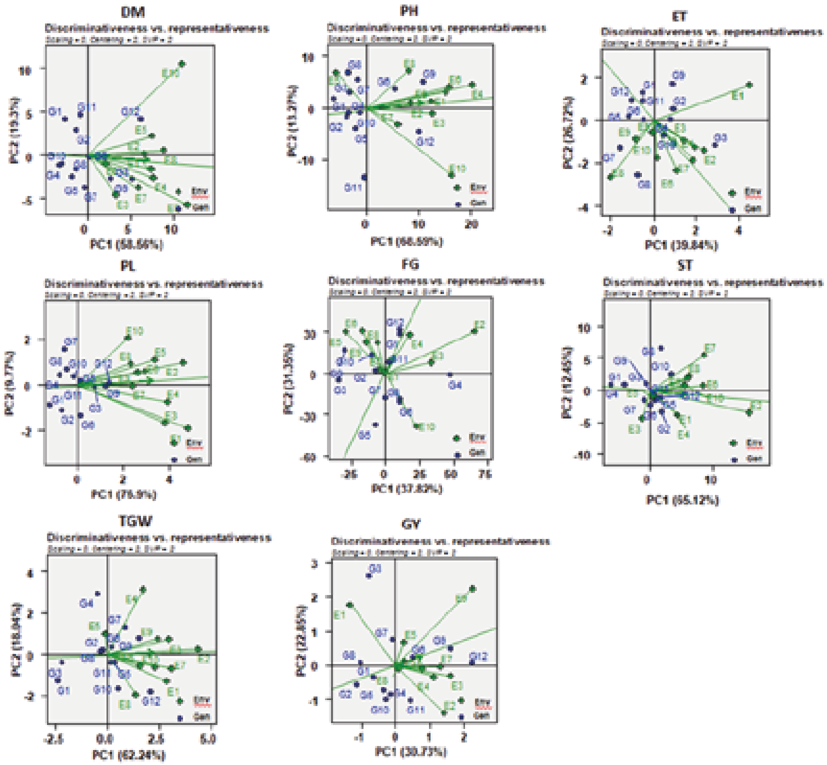

Fig. 2. Discrimination and representativeness view of the genotypic main effects plus genotype by environment interaction (GGE) biplots based on yield-component traits and grain yield data of 12 genotypes in ten environments. Green diamonds represent individual trials in 10 different environments. The average environment for each plot is indicated with a green arrow. The average-environment axis (AEA) is indicated with a thick green line passing through the biplot origin and the average environment arrow. Blue circles show individual genotypes. DM, days to maturity; PH, plant height in cm; ET, effective tillers number; PL, panicle length in cm; FG, filled grain number per panicle; ST, spikelet sterility percent; TGW, thousand-grain weight in g; GY, grain yield ton per hectare.

3.3. Polygon view of gge biplot (which-won-where pattern)

Based on 'which-won-where' patterns in GGE biplots (Fig. 3), environments were separated into prospective MEs. A polygon is formed by connecting the genotypes furthest from the biplot origin with straight lines, containing all other tested genotypes. Perpendicular lines drawn from the biplot's origin to each polygon's side divide the biplot into environment sectors. Genotypes were assigned genotype codes (G1-G12) to make them easier to identify in the plot. For DM, the ten environments were divided into two MEs: E2, E5, E5, and E10 in the first; and E1, E3, E4, E6, E7, and E9 in the second. The first sector's vertex genotype was G12 (BRRI dhan89), whereas the second sector's vertex genotype was G3 (NGR467-2). The ten environments were separated into three MEs for PH. The first ME with E5 and G8 (NGR 1161-3) was the best-performing genotype. G9 (NGR 1255-1) was the winning genotype in the second ME, which included E1, E2, E4, E6, and E8. G12 (BRRI dhan89) was the winning genotype in the third ME, which included E3, E7, E9, and E10. For ET, G3 (NGR 467-2) and G8 (NGR 1161-3) genotypes performed best in the first ME (E1, E2, E3, E4, and E7) and second ME (E5, E6, E8, E9, and E10), respectively. For PL, all environments encompassed in one sector (E1-E10) and genotypes G12 (BRRI dhan89) performed best. According to these findings, G12 (BRRI dhan89) was the winning genotype, with the longest panicle in all settings. For FG, the best-performing genotypes in the first ME (E1, E5, E6, E7, and E9), second ME (E4 and E8), third ME (E2 and E3), and fourth ME (E10) were G9 (NGR 1255-1), G1 (NGR 414-1), G4 (NGR 521-2), and G5 (NGR 522-1), respectively. For ST, the best-performing genotypes were G8 (NGR 1161-3), G10 (NGR 1308-2), and G2 (NGR 418-1) in the first ME (E7), second ME (E2, E6, E8, E9, and E10), and third ME (E1, E3, E4, and E5), respectively. For TGW, G4 (NGR 521-2) and G9 (NGR 1255-1) were the best-performing genotypes in the first ME (E4 and E5), second ME (E3 and E9), and third ME (E1, E2, E6, E7, and E8), respectively. The ten environments in GY's multiple environment trials were divided into two ME sectors. G3 (NGR 497-2) and G12 (BRRI dhan89) genotypes performed best in the first ME (E1, E5, and E6) and second ME (E2, E3, E4, E7, E8, E9, and E10), respectively. These results showed that G3 (NGR 497-2) and G12 (BRRI dhan89) were the winning genotypes, with the highest yield for the first and second MEs, respectively.

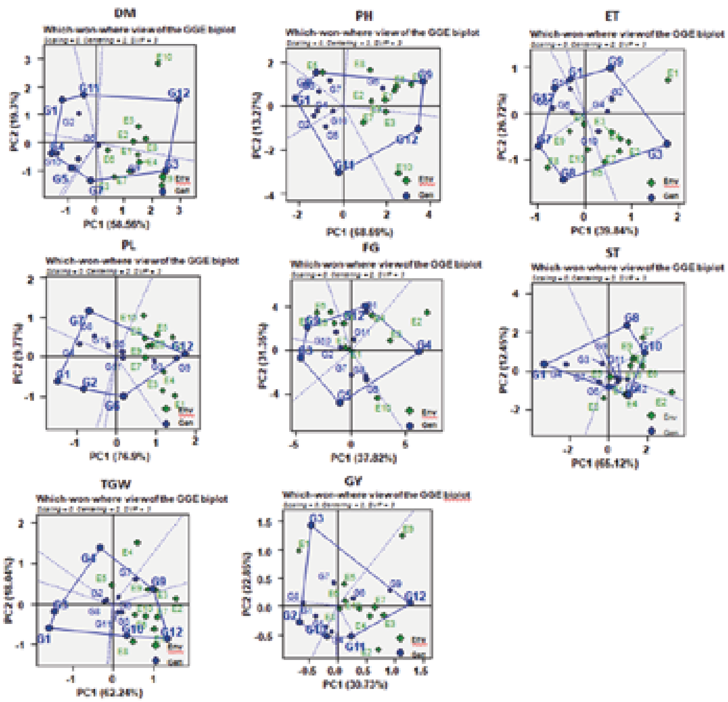

Fig. 3. DPolygon view of GGE biplot for 'which-won-where' analysis based on the yield-component traits and grain yield data of 12 genotypes in ten environments. Green diamonds represent individual trials in 10 different environments. Small and large green circles show individual genotypes and the genotypes with the highest performance, respectively. DM, days to maturity; PH, plant height in cm; ET, effective tillers number; PL, panicle length in cm; FG, filled grain number per panicle; ST, spikelet sterility percent; TGW, thousand-grain weight in g; GY, grain yield ton per hectare.

3.4. Multi-trait stability index (mtsi) analysis

All yield and quality traits, including DM, PH, ET, PL, FG, ST, TGW, and GY, were used to calculate MTSI (Table 2). The Varimax rotation criterion was used to determine the final loadings. The communality ranged from 0.746 for TGW to 0.979 for ET after Varimax rotation. The genotypes' MTSI values are displayed in Fig. 4. Based on their MTSI scores, the genotypes denoted by red color dots were selected. The order of the stable and selected genotypes was G6 (NGR 750-1), followed by G12 (BRRI dhan89) (Fig. 4).

Table 2
Communalities and selection differential of various characters based on MTSI.

Sl. No.	VAR	FA1	Communality	Uniquenesses	Xo	Xs	SD	SD (%)
1	DM	0.0118	0.853	0.147	47	59.4	12.4	26.3
2	PH	0.57	0.946	0.0543	46.7	65.9	19.2	41.0
3	ET	-0.119	0.979	0.0207	49.3	54.8	5.41	11.0
4	PL	-0.166	0.886	0.114	54.5	57.5	2.99	5.48
5	FG	0.337	0.837	0.163	44.6	64.4	19.8	44.3
6	ST	0.561	0.761	0.239	59.8	74.6	14.8	24.8
7	TGW	0.823	0.746	0.254	54.9	70.8	15.9	29
8	GY	0.891	0.856	0.144	51.7	73.6	21.9	42.4

Xo, mean of genotypes; Xs, mean of selected genotypes; SD, selection differential.

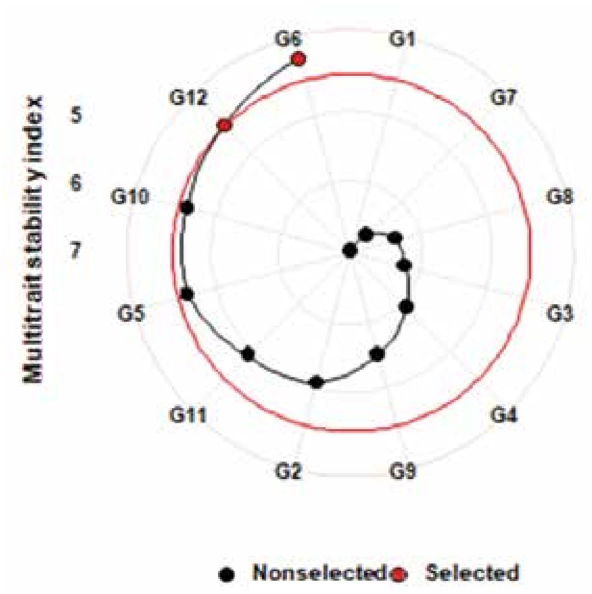

Fig. 4. Multi-trait Stability Index (MTSI) values of the genotypes.

4. Conclusions

The primary goal of plant breeders is to develop high yield potential varieties to sustain agricultural production. Such cultivars should also exhibit stable performance and broad adaptability across diverse environments. Combined ANOVA showed significant variation due to genotype, environment, and GEI for all yield related traits, with environment contributing the largest share of total variance. Thus, the environment had a strong influence on the phenotypic expression of yield components and grain yield. The AMMI biplot showed PC1 explaining over 45% of variation for most traits (except yield at 29.8%), while PC2 accounted for less than 30% for all yield –related traits. Genotypes NGR750-1 and BRRI dhan89, with near-zero scores, exhibited high stability across environments. The results indicate that the genotype NGR750-1 is stable and widely adaptable, making it a promising high yielding cultivar alternative to BRRI dhan89 for diverse agro-climatic zones of the country.

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References

Bangladesh Bureau of Statistics. (2025). Yearbook of agricultural statistics of Bangladesh. Government of Bangladesh. https://bbs.gov.bd/

Biswas, P. L., Rabbi, S. M. H. A., Akter, A., Barman, H. N., Lipi, L. F., Quddus, M. R., Saha, T., Goswami, G., & Nath, U. K. (2024). Hybrid rice research and cultivation in Bangladesh: Potentiality and prospects. International Journal of Scientific Research, 13(6), 1–9. https://doi.org/10.36106/ijsr/1925652

Cordero-Lara, K. I. (2020). Temperate japonica rice (*Oryza sativa* L.) breeding: History, present and future challenges. Chilean Journal of Agricultural Research, 80(2). https://doi.org/10.4067/S0718-58392020000200303

Dehghani, H., Ebadi, A., & Yousefi, A. (2006). Biplot analysis of genotype by environment interaction for barley yield in Iran. Agronomy Journal, 98, 388–393.

FAOSTAT. (2024). Food and Agriculture Organization statistics database. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/

FAOSTAT. (2025). Food and Agriculture Organization statistics database. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/

Freeman, G. H. (1973). Statistical methods for the analysis of genotype–environment interactions. Heredity, 31, 339–354.

Islam, M. R., Anisuzzaman, M., Khatun, H., Sharma, N., Islam, M. Z., Akter, A., & Biswas, P. S. (2014). AMMI analysis of yield performance and stability of rice genotypes across different haor areas. Eco-friendly Agricultural Journal, 7(2), 20–24.

Kang, M. S., & Pham, H. N. (1991). Simultaneous selection for high yielding and stable crop genotypes. Agronomy Journal, 83, 161–165.

Kang, M. S., & Priyadarshan, P. M. (2007). Breeding major food staples. Wiley-Blackwell.

Khatun, H., Saha, T., Biswas, P. L., Pranto, M. R. B. H., Mia, S., Maniruzzaman, S., Syed, M. A., Rashid, M. H., Eva, R. N., Chowdhury, M. T. I., Iftekharuddaula, K. M., Islam, M. R., & Khan, M. A. I. (2026). Evaluation of yield stability and adaptability of Boro rice (*Oryza sativa* L.) genotypes in Bangladesh using AMMI and GGE biplot analyses. Bangladesh Rice Journal, 28(1), 69–79. https://doi.org/10.3329/brj.v28i1.86812

McLaren, C. G., & Chaudhary, C. (1994). Use of additive main effects and multiplicative interaction models to analyse multilocation rice variety trials. In Proceedings of the FCSSP Conference (pp. 63–71). Puerto Princesa, Palawan, Philippines.

Ministry of Agriculture and Rural Development. (2010). National rice research and development strategy of Ethiopia. Ministry of Agriculture and Rural Development.

Oladosu, Y., Rafii, M. Y., Abdullah, N., Miah, G., Ramli, A., Rahim, H. A., & Usman, M. (2016). Principle and application of plant mutagenesis in crop improvement: A review. Biotechnology & Biotechnological Equipment, 30, 1–16.

Olivoto, T., & Lúcio, A. D. (2020). metan: An R package for multi-environment trial analysis. Methods in Ecology and Evolution, 11(6), 783–789. https://doi.org/10.1111/2041-210X.13384

Patra, G. L., & Mohanty, J. K. (1987). Stability of cross derivatives of groundnut. Indian Journal of Agricultural Sciences, 57, 294–298.

Prasad, K. V., & Singh, R. L. (1990). Stability analysis of yield and yield components and construction of selection indices of direct seeded rice in frost season. In Annual Review Conference Proceedings (pp. 63–71). National Agricultural Research Institute, Guyana.

Yan, W., & Kang, M. S. (2002). GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. CRC Press.

Yu, Y., Huang, Y., & Zhang, W. (2012). Changes in rice yields in China since 1980 associated with cultivar improvement, climate and crop management. Field Crops Research, 136, 65–75.

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Dry Matter Partitioning and Growth Dynamics of Two Short Duration Rice Varieties at Variable Doses of Nitrogen

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ABSTRACT

Nitrogen availability is a major factor influencing rice growth and developmental processes. The present research was conducted at the West Byde Research Field of the Bangladesh Rice Research Institute (BRRI), Gazipur to evaluate the effects of different nitrogen levels on growth dynamics and dry matter partitioning in short duration Boro rice varieties. The experiment was laid out in a randomized complete block design (RCBD) with two factors: six nitrogen levels N_0, N_{30}, N_{60}, N_{90}, N_{120}, N_{150} and two short duration rice varieties, BRRI dhan81 and BRRI dhan88 comprising twelve treatment combinations. Forty days old seedlings were transplanted with the planting geometry of 20 cm × 20 cm. Nine plants were randomly sampled from each plot at 15-day intervals to record dry matter production, growth parameters and grain yield. Dry matter partitioning and different growth parameters showed insignificant interaction for variety × nitrogen levels. However, nitrogen levels significantly influenced all evaluated parameters. Higher dry matter partitioning in leaves, culms and panicles was recorded under N_{150} and N_{120} followed by N_{60} and N_{90} across all growth stages. Growth parameters such as Leaf Area Index (LAI), Crop Growth Rate (CGR) and Net Assimilation Rate (NAR) were lowest at initial stage and reached to peak during 60-75 days after transplanting (DAT). The result indicated that nitrogen level N_{150} and N_{120} were most effective in enhancing growth and yield of rice followed by N_{60} and N_{90}. Therefore, optimum nitrogen management specially N_{120} – N_{150} produced the highest dry matter at all growth stages resulting higher grain yield followed by N_{60} and N_{90}. Growth parameters (LAI, CGR, and NAR) were lowest at the initial stage and peaked at 60–75 DAT. Overall, optimum nitrogen levels (N_{120}–N_{150}) enhanced growth dynamics more effectively and dry matter accumulation, resulting in higher grain yield in short duration rice varieties.

1. Introduction

Rice (*Oryza sativa* L.) is the staple food for about 156 million people of the country (Shelley et al., 2026) It is also the primary dietary food for nearly 50% of the world's population and supplies about 35%–60% of the dietary calories for more than three billion people, highlighting its global importance for food security (Amanullah et al., 2016). Bangladesh has a long-standing tradition of rice cultivation. The country's favorable agro-climatic conditions support rice cultivation throughout the year. The national

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average rice yield is much lower (around 3.2–3.4 t/ha) than that of other rice-growing countries (BBS, 2025). Additionally, with increasing pressure on land and natural resources, improving rice productivity through efficient crop and nutrient management remains a critical challenge. So, it is important to cultivate our arable land with very intensified way maintaining proper input. Short-duration rice varieties have gained importance due to their adaptability to intensified cropping systems and climate-resilient agriculture. Rice growth and yield determination not only influenced by genetic factors but also by efficiency of dry matter partitioning across different phenophases which is basically influences by source sink relationship (Li et al., 2023). Among the macro nutrient elements, Nitrogen requirement is higher in rice than that of other nutrients and nitrogen is one of the important limiting factors playing significant role by regulating vegetative growth, tillering ability, improving leaf area biomass accumulation and finally yield and production. On the other hand, excessive nitrogen application may lead to inefficient dry matter partitioning, prolonged vegetative growth and reduced nitrogen use efficiency, ultimately affecting yield and environmental sustainability (Saudy et al., 2023). Although atmospheric nitrogen constitutes nearly 79% of the air, it is not directly available to rice plants (Vijayakumar et al., 2022). Low efficacy of nitrogenous fertilizer is attributed mainly to ammonia volatilization, denitrification, leaching and runoff losses (Cho, 2003). Nitrogen is involved in all the metabolic processes in plants and about 75% of leaf N is associated with chloroplast, which are essential for dry matter production during photosynthesis (Mae, 1997). High nitrogen availability to the plant has been associated with increase in plant height, high chlorophyll content and leads to increase productivity (Garnier et al., 1995). Short duration rice varieties exhibit noticeable growth patterns; unique nitrogen requirements compared to long duration cultivars (Chen et al., 2022). Understanding their growth behavior and dry matter accumulation under different levels of nitrogen is essential for optimizing nutrient management practices and maximizing productivity within limited growing periods. Dry matter accumulation and its partitioning among plant organs are dynamic processes that vary with phenological stages of rice growth stages. Efficient partitioning of assimilates from source organs to sink tissues is essential for yield formation. Moreover, nitrogen is the important source to increase the dry matter production which ultimately partitioned into the grain yield. Therefore, the present study was undertaken to quantify growth rates at different phenophases of two short-duration rice varieties under varying nitrogen levels. The outcomes of this research are expected to provide physiological insights to support improved nitrogen management strategies for short-duration rice cultivation.

2. Materials and methods

2.1. Experimentation

The experiment was conducted at Bangladesh Rice Research Institute (BRRI) research farm, Gazipur (23°85.9′ N and 90°82.4′ E), Bangladesh, during Boro rice season, 2022-23. Two short-duration rice varieties, BRRI dhan81 and BRRI dhan88 were evaluated under six nitrogen levels: N0, N30, N60, N90, N120, N150. The experiment was designed with Randomized Complete Block Design (RCBD) and total replications was three. The recommended doses of other fertilizers (P–K–S–Zn) were applied at rates of 60–120–56–5 kg ha^{-1}, respectively. All fertilizers were applied as a basal dose, except nitrogen, which was top-dressed in three equal splits. Forty-day-old seedlings were transplanted in January 2022 with a spacing of 20 cm × 20 cm in plot measuring 2.5 m × 6 m.

2.2. Site description

The soil of the experimental site was clay loam in texture, slightly alkaline in reaction (pH, 6.7), non-saline (ECe, 1.02 dS/m), medium fertile soil containing organic carbon (1.18%), total N (0.15%), exchangeable K 0.13 meq/100 g soil, available S 14 mg/kg and available Zn 1.5 mg/kg.

2.3. Data recording and handling

Nine plants were taken randomly from each plot as representative sample for dry matter production and other growth parameter data mostly at 15 days' interval after transplanting. The samples were cleaned, separated into leaves, culm and panicle and then oven-dried at 70 º C until a constant weight is obtained and dry weight of leaves, culm and panicle were recorded separately in gm^{-2}. Total dry weight was calculated as the sum of dry weights of the plant components. At harvest yield data were recorded from an area of 5 square meter. Leaf area(LA) and leaf area index (LAI) were measured according to Gomez et al. (1972). Physiological growth parameters were calculated using successive sampling data following the methods described by Watson (1952).

$$\textit{Leaf area index (LAI)} = \frac{\textit{Leaf Area (A)}}{\textit{Ground Agea (P)}}$$

$$\textit{Grop growth rate (CGR)} = \frac{W2 - W1}{P\,(T2 - T1)}\ g\ m^{-2}\ day^{-1}$$

Where,

W_1 = Dry weight of plant m^{-2} at time T_1

W_2 = Dry weight of plant m^{-2} at time T_2

P = Ground area (m_2)

T_1 and T_2 are the two consecutive time period

$$\textit{Relative growth rate (RGR)} = \frac{LnW2 - LnW1}{T2 - T1}\ g\ g^{1}\ day^{-1}$$

Where,
W_1 = Dry weight of plant m^{-2} at time T_1
W_2 = Dry weight of plant m^{-2} at time T_2
Ln = Natural log
T_1 and T_2 are the two consecutive time period

$$Net\ assimilation\ rate\ (NAR) = \frac{W2 - W1}{T2 - T1} \times \frac{1}{LA}$$

Where,
W_1 = Dry weight of plant m^{-2} at time T_1
W_2 = Dry weight of plant m^{-2} at time T_2
T_1 and T_2 are the two consecutive time period
LA = Leaf area

2.4. Statistical analysis

Data were analyzed using RStudio version 4.0. Factorial ANOVA was performed to evaluate the effects of rice varieties, nitrogen levels and their interaction on growth parameters at different growth stages of short duration rice varieties. Treatment means were compared using the Critical Difference (CD) test at a 5% level of significance. Graphical representations of the results were prepared using Microsoft Excel 2010.

3. Results and discussion

3.1. Dynamics of dry matter accumulations

Dry matter accumulation is a crucial determinant of grain yield in rice. The enhancement of rice yield potentiality might come from the increased dry matter production. Total dry matter production varied significantly due to the effect of N-levels at different growth stages. Total dry matter production (TDM) increased progressively with the increase of growth stages and N-levels. The application of N fertilizer alone and in combination with P effectively promote dry matter accumulation, translocation across growth stages and increase yield (Qin et al., 2025).

The interaction effect between variety and nitrogen level was insignificant for culm, leaf and panicle dry matter production at different growth stages. However, nitrogen levels exerted a significant effect on dry matter accumulation. At 30 DAT the highest culm and leaf dry matter was obtained with N150. Culm dry matter at N_{30}, N_{60} N_{90} and N_{120} level was similar. Lowest culm and leaf dry matter was produced by N0. At 60 DAT, culm and leaf dry matter production was higher in N_{150} followed by N_{120} than other treatment. However, culm and leaf dry matter was the lowest at N0 followed by N_{30} level. At 75 DAT the highest culm dry matter was obtained with N_{150} and N_{120}. Culm dry matter was statistically similar at nitrogen level N60 and N_{90}. However, lowest culm dry matter was found in N_{30} and N_0. Leaf dry matter was highest under the treatment N_{150} followed by N_{120} and N_{90}. Lowest leaf dry matter was observed in nitrogen level N_0 followed by N_{30} and N_{60}. At this stage panicle weight was higher in the treatments with N_{150} nitrogen level. However, lowest panicle weight was obtained with nitrogen level N_0. At 90 DAT, culm dry matter production was higher in nitrogen level N_{150} which was statistically similar with N_{120} and N_{90}. Leaf and panicle dry matter production was observed highest in N_{150} followed by N_{120}. The rapid growth of dry matter at the higher nitrogen level may be due to the robust growth of plants (Fig. 1).

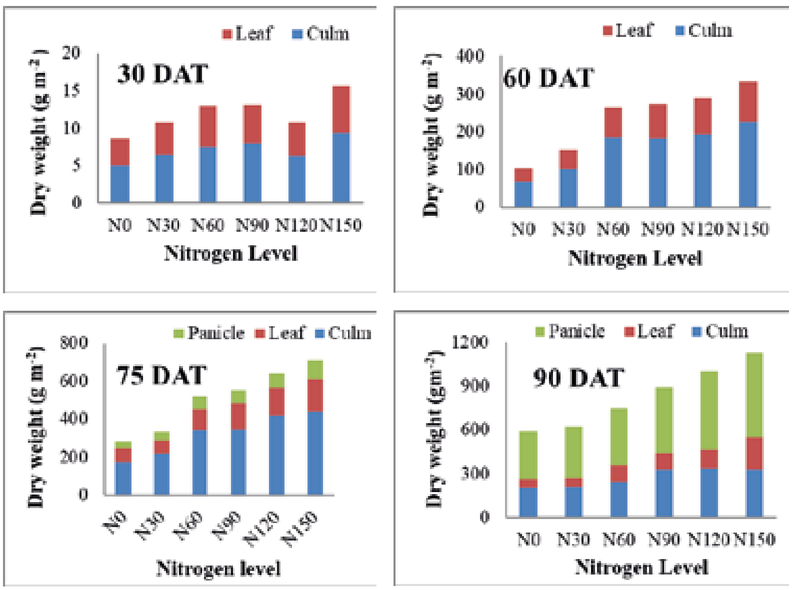

Fig.1. Dry matter partitioning (g m^{-2}) in rice at different days after transplanting.

3.2. Correlation studies of TDM with grain yield

The results demonstrated a positive correlation between total dry matter production at 30, 60, 75 and 90 DAT grain yield of the tested rice varieties which indicates that grain yield was greatly influenced by total dry matter production (Fig. 2). At 30 DAT (early vegetative stage), plants have low total biomass, but this period is crucial for setting up the "framework" of the plant, including root system development, leaf area expansion, and tiller number. Small, early increases in dry matter directly contribute to increased photosynthetic capacity (higher Leaf Area Index) and enhanced ability to acquire nutrients and water. This directly influences final yield potential, leading to a high "slope" in the relationship between biomass increase and yield, as shown in studies where early growth parameters were the best estimators of yield. By 60 DAT, plants have already accumulated significant biomass, and the structure of the plant is largely established. At this stage, each additional unit of biomass typically represents "filler" material or stems rather than productive, high-efficiency photosynthetic machinery, resulting in a lower marginal yield increase (lower slope). This dynamic reflects the logistic nature of plant growth, where the rate of biomass accumulation is highest in the middle, but the impact of that accumulation on final yield is highest during early development (Castaño et al., 2026).

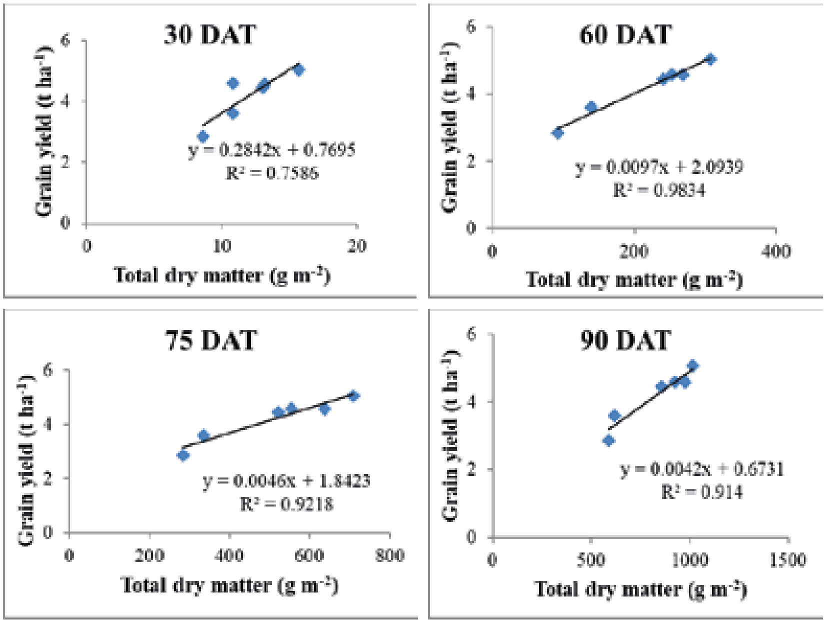

Fig. 2. Relationship between total dry matter production and grain yield in rice at different days after transplanting.

3.3. Leaf area index

Leaf area index is important physiological parameters which accounts for the production of photosynthate and finally determines crop yield because it influences the light interception by the crop canopy (Fageria et al., 2006). Interaction effect of variety and nitrogen level for leaf area index was insignificant for all growth stage except 90 DAT. The average leaf area index (LAI) of the rice increased gradually up to 60 DAT and thereafter it increased sharply reaching a peak value at 90 DAT that is heading or flowering, but there after it decreased gradually towards maturity due to senescence of leaves. The LAI of rice increases as crop growth advances and reaches a maximum at about heading or flowering (Yoshida, 1981). The LAI reached the maximum in the heading stage and then declined until the maturity stage (Qi et al., 2024). Significant effect of nitrogen level was found for all growth stages except 30 DAT. Leaf area index was higher in nitrogen level N_{150}, N_{120} and N_{90} and N_{60} at 60 DAT, 75 DAT and 90 DAT irrespective of varieties. At maturity stage N_{120} and N_{150} produced the highest leaf area index. Higher leaf area index may be due to the higher number of leaves and increased leaf area. Navinkumar et al. (2018) also reported that the higher LAI was associated with the increased tiller production and size of the leaves. However, for all the treatment combination LAI was lower than the average. This may be due to low nitrogen supply. LAI at maximum tillering in rice typically ranges around 3–5 under optimal conditions, but can fall below 3 when nitrogen is limited or under suboptimal management (Yoshida., 1981) (Table 1).

Table 1

Leaf area index of rice as influenced by varieties and nitrogen levels at different DAT.

Treatments	**Leaf area index (LAI)**			
Varieties	**30 DAT**	**60 DAT**	**75 DAT**	**90 DAT**
BRRI dhan81	0.05	1.05	2.09	1.36
BRRI dhan88	0.06	1.18	2.19	0.67
SED ±	0.01	0.089	0.253	0.147
CD at 5%	NS	NS	NS	0.303
Nitrogen (N) (kg ha^{-1})				
N_0	0.05	0.43	1.03	0.50
N_{30}	0.07	0.79	1.23	0.44
N_{60}	0.07	1.09	2.01	0.62
N_{90}	0.05	1.39	2.59	1.23
N_{120}	0.05	1.29	2.83	1.79
N_{150}	0.07	1.69	3.17	1.52
SED ±	0.018	0.154	0.439	0.255
CD at 5%	NS	2.06	0.90	0.526
Interaction (V × N)				
SED ±	0.025	0.218	0.62	0.36
CD at 5%	NS	NS	NS	0.743

3.4. Crop growth rate

Insignificant interaction was present between variety and nitrogen level for this trait. No significant interaction was observed among treatments combination for CGR. Both varieties showed almost similar growth patterns across the nitrogen levels from N_0 to N_{150}. Nitrogen mainly affected the magnitude of growth, but it did not change the growth pattern over time. Since the treatments were applied at 30 DAT and data were collected at 15-day intervals, the growth pattern remained nearly similar across treatments, resulting in an insignificant interaction (Ronanki et al., 2017; Sridhar et al., 2019). Crop growth rate was very minimum at the initial stage as 0-30 DAT which increased gradually towards the growth stages. It reached to peak at flowering stage and then decreased gradually to 75-90 DAT as harvest. With the increase of leaf area over time, CGR also increased until 60 DAT and then declined at 80 DAT in all cultivars (Kaysar et al., 2022). Higher crop growth rate was obtained with nitrogen level N_{120} and N_{150} at 0-30 DAT. Significant effect of nitrogen level was found for 30-60 DAT and 60-75 DAT. At 30-60 DAT and 60-75 DAT highest crop growth rate was observed in N_{120} and N_{150} nitrogen level. However, at 75-90 DAT CGR decreased drastically. Higher CGR may be due to the higher LAI produced by this nitrogen level. Lower CGR in the initial growth stage appears to be mainly due to low leaf area, while higher CGR at flowering and grain development stages may be due to higher LAI and decrease in CGR towards maturity may be attributed to decrease in leaf area as a result of senescence of leaves (Sridhar et al., 2019) (Fig. 3 and Table 2).

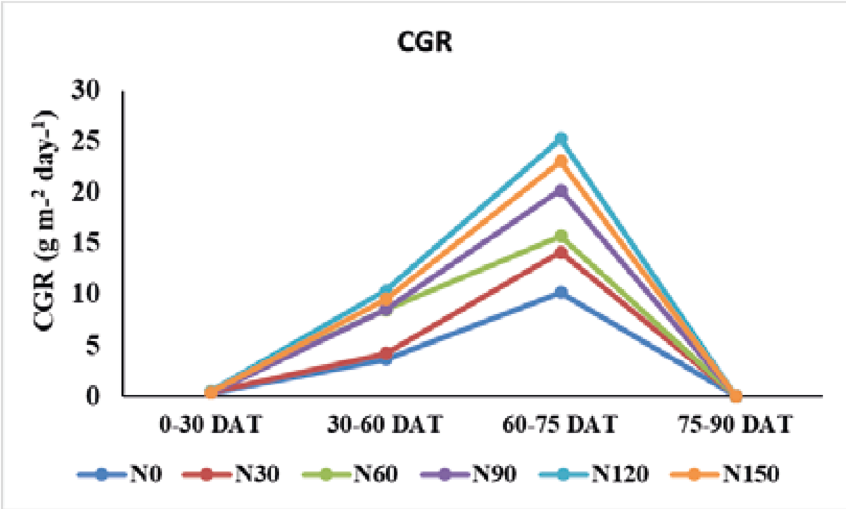

Fig. 3. Effect of various nitrogen treatments on crop growth rate (g m^{-2} day^{-1}) at different intervals.

Table 2
Crop growth rate of rice as influenced by varieties and nitrogen levels at different DAT.

Treatments	**Crop growth rate (g m^{-2} day^{-1})**			
Varieties	**0-30 DAT**	**30-60 DAT**	**60-75 DAT**	**75-90 DAT**
BRRI dhan81	0.36	6.91	17.50	0.03
BRRI dhan88	0.44	7.98	18.64	0.03
SED ±	0.047	0.481	2.812	0.006
CD at 5%	NS	0.992	NS	NS
Nitrogen (N) (kg ha^{-1})				
N_0	0.34	3.62	14.15	0.03
N_{30}	0.38	4.22	10.02	0.04
N_{60}	0.48	8.51	15.71	0.02
N_{90}	0.30	8.46	20.20	0.03
N_{120}	0.49	10.35	25.28	0.03
N_{150}	0.40	9.50	23.06	0.03
SED ±	0.082	0.833	4.871	0.01
CD at 5%	NS	1.719	10.05	NS
Interaction (V × N)				
SED ±	0.12	1.17	6.88	0.014
CD at 5%	NS	NS	NS	NS

3.5. Net assimilation rate (NAR)

NAR is the increase in plant dry mass per unit leaf area per unit time. It is the physiological potential for converting the total dry matter into grain yield. The interaction effect between variety and nitrogen level was not significant. Both varieties followed similar growth patterns for NAR across nitrogen levels (N_0–N_{150}), where nitrogen influenced growth magnitude but not its trend over time, leading to an insignificant interaction (Sridhar et al., 2019). Significant influence of nitrogen level was only observed for net assimilation rate at 75-90 DAT. At 75-90 DAT highest NAR was observed in N60 nitrogen level followed by N_{120} and N_{150}. NAR was low at initial growth stage that is 0-30 DAT and 30-60 DAT. Then it increased linearly upto 60-75 DAT. Finally, it dropped to maturity that is 75-90 DAT for all treatments. The increase NAR during the active growth stages may be attributed to higher LAI and dry matter production with those stages (Table 3). The Higher net assimilation rate with the growth stages was due to higher LAI and dry matter production with those stages (Willians et al., 1946). Sharma et al. (2022) also stated that the maximum NAR was attributable to higher LAI and dry matter production as compared to other varieties.

Table 3

Net assimilation rate of rice as influenced by varieties and nitrogen levels at different DAT.

Treatments	**Net assimilation rate (mg m^{-2} day^{-1})**			
Varieties	**0-30 DAT**	**30-60 DAT**	**60-75 DAT**	**75-90 DAT**
BRRI dhan81	0.67	0.78	0.97	3.1
BRRI dhan88	0.76	0.62	0.88	3.5
SED ±	0.00	0.00	0.00	1.0
CD at 5%	NS	0.00	NS	NS
Nitrogen (N) (kg ha^{-1})				
N_0	0.66	0.70	1.35	2.0
N_{30}	0.73	0.68	0.90	3.0
N_{60}	0.83	0.80	0.93	7.3
N_{90}	0.76	0.66	0.98	4.0
N_{120}	0.66	0.78	0.71	5.0
N_{150}	0.65	0.58	0.70	5.0
SED ±	0.00	0.00	0.00	1.0
CD at 5%	NS	NS	NS	2.0
Interaction (V × N)				
SED ±	0.00	0.00	0.00	2.0
CD at 5%	NS	NS	NS	NS

3.6. Relative growth rate

The rate at which a plant incorporates new material of dry matter accumulation into its sink is measured by RGR and is expressed in g g^{-1} day^{-1}. Insignificant interaction effect of variety and nitrogen level was observed for this trait. Both varieties exhibited similar relative growth rate across nitrogen levels (N_0–N_{150}), where nitrogen affected the magnitude of RGR but did not change its growth trend, resulting in an insignificant interaction. Respiration depends on total biomass, but photosynthesis depends only on photosynthetic biomass, so biomass builds up more slowly as total biomass increases. (Wopereis et al., 1996). RGR was maximum at 30-60 DAT and then it was decreased gradually towards 60-75 DAT. Verma et al. (2023) also found similar observations. After that it become very low to maturity stage that is 75-90 DAT. Kaysar et al. (2022) reported that RGR was higher in the early stages and began to decline as the plants got older. Maximum RGR was obtained with nitrogen level N_{150}, N_{120}, N_{60} and N_{30}. Maximum RGR at 30-60 DAT was mainly due to the higher accumulation of photosynthetic biomass started and then it tends to decrease towards growth stages due to the incretion of non-photosynthetic biomass (Table 4).

Table 4
Relative growth rate of rice as influenced by varieties and nitrogen levels at different DAT.

Treatments	Relative growth rate (g g^{-2} day^{-1})		
Varieties	30-60 DAT	60-75 DAT	75-90 DAT
BRRI dhan81	0.09	0.05	0.03
BRRI dhan88	0.09	0.04	0.03
SED ±	0.004	0.006	0.006
CD at 5%	NS	NS	NS
Nitrogen (N) (kg ha^{-1})			
N_0	0.08	0.06	0.03
N_{30}	0.10	0.05	0.04
N_{60}	0.10	0.05	0.02
N_{90}	0.08	0.04	0.02
N_{120}	0.10	0.04	0.03
N_{150}	0.10	0.05	0.03
SED ±	0.008	0.001	0.01
CD at 5%	0.01	NS	NS
Interaction (V × N)			
SED ±	0.011	0.015	0.015
CD at 5%	NS	NS	NS

Grain yield (t ha^{-1}): Grain yield had significant effect for nitrogen level. Zhou et al. (2023) stated that yield has significant and positive correlation with dry matter accumulation (DMA) and and N accumulation from heading stage to maturity stage. However, interaction effect was observed insignificant for this trait. The insignificant interaction effect on grain yield suggests that the response of both varieties to nitrogen levels (N_0–N_{150}) was similar across treatments. Nitrogen application influenced yield to a certain extent, but it did not differentially affect the varieties, resulting in an insignificant interaction. The highest grain yield was produced at nitrogen level N150 followed by N_{120}, N_{90} and N_{60} where as the lowest yield production was obtained with nitrogen level N0 (Fig. 4). Bhowmick et al. (2000) reported that increase in grain weight at higher nitrogen rates might be primarily due to increase in chlorophyll content of leaves which led to higher photosynthetic rate and ultimately plenty of photosynthates available during grain development.

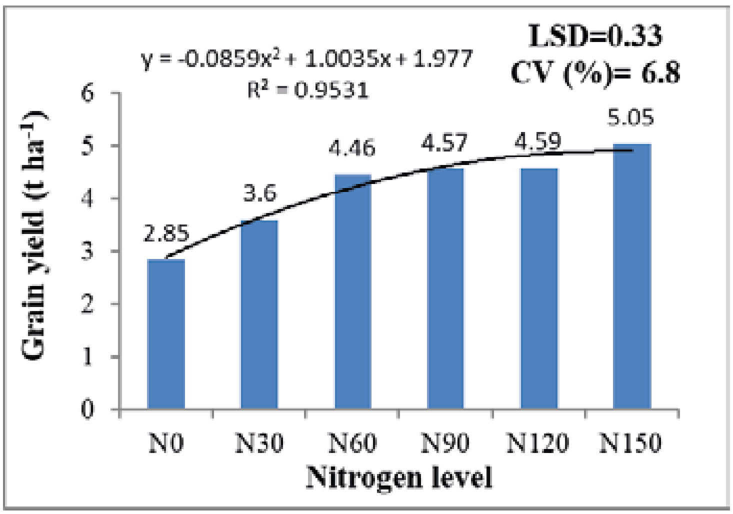

Fig. 4. Grain yield production at variable nitrogen level.

4. Conclusion

The interaction effect between variety and nitrogen level on dry matter partitioning and several growth factors was insignificant. However, nitrogen application significantly influenced growth dynamics, dry matter partitioning, and grain-yield of short duration rice varieties. Higher nitrogen levels, especially N120 and N150, promoted greater dry matter accumulationin leaves, culms and panicles throughout all growth stages. Total dry matter production was strongly correlated with grain yield indicating the importance of biomass accumulationin yield formation. Growth parameters, such as LAI, CGR, and NAR were lowest during the initial growth stages and reached their peaked between 60 and 75 DAT. Overall, nitrogen levels N150 and N120 proved most effective in maximizing physiological growth and grain yield, followed by N90 and N60, representing the crucial role of optimum nitrogen management for maximizing rice productivity of short-duration Boro rice varieties.

Conflicts of Interest

The authors declare no conflicts of interest regarding publication of this paper.

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References

Amanullah, I. (2016). Dry matter partitioning and harvest index differ in rice genotypes with variable rates of phosphorus and zinc nutrition. Rice Science, 23(2), 78.

Bangladesh Bureau of Statistics. (2025). Statistical yearbook of Bangladesh 2024. Ministry of Planning, Government of the People's Republic of Bangladesh.

Bhowmick, N., & Nayak, R. L. (2000). Response of hybrid rice (*Oryza sativa*) varieties to nitrogen, phosphorus and potassium fertilizers during dry (boro) season in West Bengal. Environment and Ecology, 18(2), 323-326.

Cho, J. Y. (2003). Seasonal runoff estimation of N and P in a paddy field of central Korea. Nutrient Cycling in Agroecosystems, 65(1), 43-52.

Chen, J., Cao, F., Liu, Y., Tao, Z., Lei, T., Abou-Elwafa, S. F., & Huang, M. (2022). Comparison of short-duration and long-duration rice cultivars cultivated in various planting densities. Agronomy, 12(8), 1739.

Castaño, G., Barragán-Hernández, W., Mahecha-Ledesma, L., & Angulo-Arizala, J. (2026). Phenological and nutritional dynamics of Tithonia diversifolia across harvest intervals in tropical mid altitudes. Agroforestry Systems, 100(3), 83.Fageria, N. K., Baligar, V. C., & Li, Y. C. (2008). The role of nutrient efficient plants in improving crop yields in the twenty first century. Journal of plant nutrition, 31(6), 1121-1157.Gomez, K. A. (1972). Techniques for field experiments with rice. International Rice Research Institute

Garnier, E., Gobin, O., & Poorter, H. (1995). Nitrogen productivity depends on photosynthetic nitrogen use efficiency and on nitrogen allocation within the plant. Annals of Botany, 76(6), 667-672.

Kaysar, M. S., Sarker, U. K., Monira, S., Hossain, M. A., Haque, M. S., Somaddar, U., ... & Uddin, M. R. (2022). Dissecting the relationship between root morphological traits and yield attributes in diverse rice cultivars under subtropical condition. Life, 12(10), 1519.

Li, X., Zhou, Y., Shuai, P., Wang, X., Peng, S., & Wang, F. (2023). Source–sink balance optimization depends on soil nitrogen condition so as to increase rice yield and N use efficiency. Agronomy, 13(3), 907.

Mae, T. (1997). Physiological nitrogen efficiency in rice: nitrogen utilization, photosynthesis, and yield potential. Plant and soil, 196(2), 201-210.

Navinkumar, C., Thavaprakaash, N., Dheebakaran, G., Jegadeeswari, D., & Panneerselvam, S. (2018). Effect of varieties and methods of planting on performance of rice under organic farming. Madras Agriccultural Journal, 105 (7-9), 271-275.

Page, A. L., Miller, R. H., & Keeney, D. R. (1982). Methods of soil analysis. Part 2. American Society of Agronomy. Soil Science Society of America, 4(2), 167-179.

Qi, D., Chen, S., Yue, W., & Duan, Y. (2024). Leaf senescence characteristics and economic benefits of rice under alternate wetting and drying irrigation and blended use of polymer-coated and common urea. Frontiers in Plant Science, 15, 1444819.

Qin, X., Rao, X., Liu, H., Hong, J., Tang, W., Yan, S., ... & Hu, Y. (2025). Effect of Nitrogen and Phosphorus Fertilizers on Dry Matter Accumulation and Translocation of Two Amylose Content Indica Rice on Yield. Plants, 14(10), 1536.

Ronanki, S., Rani, P. L., Madhavi, A., Sreenivas, G., & Raji Reddy, D. (2017). Dry matter accumulation, partitioning and nitrogen uptake of transplanted rice under varied plant densities and nitrogen levels. Chemical Science Review and Letters, 23(6), 1975-1979.

Saudy, H. S., & Mohamed El–Metwally, I. (2023). Effect of irrigation, nitrogen sources, and metribuzin on performance of maize and its weeds. Communications in Soil Science and Plant Analysis, 54(1), 22-35.

Sharma, A., Sharma, P. B., Vishwakarma, S. K., Sahu, R. P., & Ahirwal, A. (2022). Physiological Parameters of different Rice varieties Grown under Organic Production System. Biological Forum—An International Journal, 14(2), 57–62.

Shelley, I. J., Takahashi-Nosaka, M., Kano-Nakata, M., Haque, M. S., & Inukai, Y. (2016). Rice cultivation in Bangladesh: present scenario, problems, and prospects. Journal of International Cooperation for Agricultural Development, 14, 20-29.

Sridhar, K., Srinivas, A., Kumar, A. K., Ramprakash, T., & Rao, R. P. (2019). Physiological growth parameters of rabi rice (Oryza sativa L.) under alternate wetting and drying irrigation with varied nitrogen levels. International Journal Of Current Microbiology and Applied Sciences, 8(1), 1-15.

Vijayakumar, S., Lokesh Goud, D., Hareesh Reddy, C. H., Mahender Kumar, R., & Sundaram, R. M. (2022). Efficient nitrogen management technologies for sustainable rice production. Journal Of Rice Research, 15, 1-19.

Verma, R., Singh, A. K., Maurya, S., Prakash, R., & Singh, D. (2023). Effects of Nutrient Management on Growth Indices and Grain Yield of Different Crop Establishment Methods in Rice (Oryza sativa L.). International Journal of Plant Soil Science, 35(16), 67-73.

Watson, D. J. (1952). The physiological basis of variation in yield. Advances in agronomy, 4, 101-145.

Williams, R. F. (1946). The physiology of plant growth with special reference to the concept of net assimilation rate. Annals of Botany, 10(37), 41-72.

Wopereis, M. C. S., Kropff, M. J., Maligaya, A. R., & Tuong, T. P. (1996). Drought-stress responses of two lowland rice cultivars to soil water status. Field Crops Research, 46(1-3), 21-39.

Yoshida, S. (1981). Fundamentals of rice crop science. International Rice Research Institute, 269.

Zhou, S., Liu, K., Zhuo, X., Wang, W., Zhang, W., Zhang, H., ... & Liu, L. (2023). Optimizing nitrogen regime improves dry matter and nitrogen accumulation during grain filling to increase rice yield. Agronomy, 13(8), 1983.

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Nitrogen Use Efficiency of Modern Rice Variety Influenced by Integrated Nutrient Management Options in Dry Season

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Harvest index

A B S T R A C T

Nitrogen (N) is the most limiting nutrient element affecting yield and performances of modern rice varieties. However, efficient use of nitrogen by a modern rice variety might be improved through integrated fertilizer management options. To explore this, a field experiment was conducted over two consecutive dry seasons (2021-22 and 2022-23) from December to June at the experimental field of Sher-e-Bangla Agricultural University (SAU), Dhaka, Bangladesh. Modern rice variety, BRRI dhan100 was used in the experiment. The objectives of the experiments were to investigate the responses of BRRI dhan100 under different N fertilizer rates as well as to assess N use efficiencies of the variety. The experiment comprised seven treatments such as N1= Researcher's Practice (RP): N-P-K-S- Zn @ 124-22-75-20-4 kg ha^{-1}, N_2 = N_1 + 33% more N over N_1, N_3 = N_1 – 33% less N than N_1, N_4 = N_1 but no nitrogen was used (-N), N_5 = N_1 + Cowdung @ 5 t ha^{-1}, N_6 = Soil test based (STB) dose: N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1} and N_7 = Absolute control (No fertilizers applied). The experimental design was RCB (randomized complete block) with three replicates. Standard management practices were maintained across treatments. Yield and yield components data were collected following standard methods at maturity. Collected grain and straw samples were analyzed to estimate N use efficiencies. The treatments had significant ($p<0.01$ to 0.05) effects on yield, yield components, and N use efficiencies of BRRI dhan100 in both years. Among the treatments, N_1, N_5 and N_6 showed statistically similar performances of BRRI dhan100 in respect of yield, yield components and nitrogen efficiencies. Irrespective of years, the highest mean grain yield (6.76-6.83 t ha^{-1}) was obtained from N_5 (N_1 + Cowdung), which were statistically identical with those in N1 (Researcher's Practice: RP) and N_6 (STB) but significantly ($p<0.01$) higher than other four treatments (N_2, N_3, N_4 and N_7). N use efficiencies of BRRI dhan100 were significantly (p = 0.01) affected by the treatments. Agronomic (AEN: 21.63 to 23.98 kg grain kg^{-1} applied N) and physiological efficiencies (PEN: 36.99 to 40.36 kg grain kg^{-1} N uptake) of N_1, N_5 and N_6 were statistically identical but significantly ($p<0.01$) higher than that in N_2 and N_3. Therefore, considering overall performances especially grain yield and nitrogen use efficiencies, BRRI dhan100 may be grown applying the fertilizer treatments N_1 (Researcher's Practice: RP), N_5 (N1 + 5 t ha^{-1} Cowdung) and N_6 (STB) to achieve higher yield, improve N use efficiencies ensure food security of the country and expectantly to maintain soil health.

1. Introduction

Rice (*Oryza sativa* L.) is the most important staple food crop, feeding more than half of the global population, and ranks as the second most widely traded agricultural commodity worldwide (Gondwal et

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al., 2024; Jahan et al., 2017). It plays a vital role in ensuring food security, particularly in economically developing nations (Dass et al., 2016; Wasaya et al., 2022). Globally rice is grown in ~164.19 million hectares of land producing ~756.74 million tons per year (World Food and Agriculture – Statistical Yearbook, 2023). In Bangladesh, rice is grown in three distinct seasons i.e. Boro/dry (Dec-May), Aus (Apr-Aug), and Aman (Jul-Dec) covering almost 11.7 million hectares of land (World Food and Agriculture – Statistical Yearbook, 2022). Sustenance and enhancement in rice production of Bangladesh is a major challenge due to the continual loss of cultivable land, which is declining at a rate of approximately 0.7% per year (Statistical-Yearbook-of-Bangladesh, 2019). This requires either vertical increase by increasing yield and productivity per unit area through improve management practices and cropping intensity or horizontal increase by exploring new area for rice cultivation which is very difficult in Bangladesh with land scarcity. The average rice yield in Bangladesh (3.25 t ha^{-1}) remains lower compared to other major rice-producing countries such as China (4.74 t ha^{-1}) and Japan (5.00 t ha^{-1}) (World Food and Agriculture – Statistical Yearbook, 2022). However, lower yield has not indicated by low yield potentiality instead it can be influenced by several biotic and abiotic factors (Mahbub et al., 2017; Singh et al., 2014). Among abiotic factors N fertilizer management is the most important factors for rice cultivation. Nitrogen (N) is an essential macronutrient and integral part of genetic material, amino acids, chlorophyll, and proteins (Anas et al., 2020; Azimi et al., 2021) via its involvement in the photosynthesis, enzyme activity and carbon–nitrogen metabolism (Anas et al., 2020; Ma et al., 2022). Hence, efficient N management in high-yielding rice cultivars is essential to achieve their genetic yield potential (Jahan et al., 2022; Mahajan et al., 2010; Rezaei et al., 2009). Therefore, determining the optimal N rate and evaluating nitrogen use efficiency (NUE) for each rice variety is vital for fertilizer recommendations (Noor, 2017).

Generally N use efficiency is defined as the N output by the crop per unit nitrogen input (Meena et al., 2014; Mitra, 2017). Inefficient or imbalanced N fertilizer application reduces N utilization efficiency, decreases yield, deteriorates grain quality, and contributes to environmental pollution, posing risks to human health and sustainable agriculture (Lü et al., 2009). Appropriate fertilizer management can remarkably enhance rice yield and quality (Mahender et al., 2016), whereas excessive use of fertilizers especially N fertilizer diminishes NUE and increases N losses. As such higher N application rates increase pest incidence and intensify the risk of nitrogen losses through volatilization, leaching and denitrification, leading to environmental degradation, global warming and health hazards (Thorburn et al., 2017; Hu et al., 2018). Balance N, P, K, S and Zn fertilizers application in producing good rice yield is crucial and efficient use of nutrients especially N is important to sustain rice production and healthier environment. In Bangladesh, N requirement for paddy rice is approximately 80 kg N ha^{-1}, but due to limited knowledge of N mineralization, farmers generally rely exclusively on costly mineral N fertilizers, which typically have an efficiency of less than 40% (Kader et al., 2013). In many rice-growing regions, fertilizer recommendations follow generalized prescriptive models that do not consider site-specific variations in soil N-supplying capacity or varietal requirements (Fan et al., 2012; Kader et al., 2013, 2017; Meisinger et al., 2008). Such blanket recommendations often lead to inefficient N use, increased production costs, yield decline, and environmental pollution (Fan et al., 2012; Peng et al., 2009). Total N was found to inconsistently relate to indigenous soil N supplying capacity (Kader et al., 2013), however, previous studies have primarily focused on yield response to N rates and mechanisms of N loss, rather than optimizing fertilizer rates in line with the soil's inherent N-supplying ability (Saha et al., 2012 and Zhao et al., 2010). Several studies have assessed NUE among rice genotypes globally (Karmakar et al, 2021; Wu et al., 2016; Haefele et al., 2008), but limited research has been conducted with newly released modern rice variety, BRRI dhan100 with only chemical and integrated nutrient fertilizer management to evaluate its N use efficiency and performance. Therefore, this study was conducted to evaluate performances and nitrogen use efficiency (NUE) of BRRI dhan100 with fertilizers management options including chemical and integrated fertilizer management practices during dry (Boro) season.

2. Materials and methods

2.1. Experimental site, weather and soil

The field experiments with same treatments were carried out for two consecutive years (December 2021 to May 2022 and December 2022 to May 2023) at the experimental field of Sher-e-Bangla Agricultural University, Sher-e-Bangla Nagar, Dhaka (Latitude: 23°46´19.9´´N, Longitude: 90°22´15.1´´ E and Altitude: 9.0 m above from sea level). The experimental site has fallen under subtropical climatic condition with high temperatures and humidity, moderate rainfall and occasional winds during the kharif season (March-September), as well as low temperatures and limited precipitation in the rabi season (October-February) (BMD, 2024).

2.2. Soil properties of the experimental site

The experiment was carried out in typical rice growing silty clay loam soil at the Soil Science Division experimental field at SAU, Dhaka. The physical and chemical properties of the surface soil (0-20 cm) are shown in the Table 1.

Table 1
Physical and chemical properties of the initial soil (0-20 cm depth).

Characteristics	Value
% Sand (2.0-0.05 mm)	19
% Silt (0.05-0.002 mm)	45
% Clay (<0.002 mm)	36
Textural class	Silty Clay Loam
Consistency	Granular and friable when dry
pH-H_2O (1: 2.5)	6.1
Organic Matter (%)	1.38
Total N (%)	0.09
Available P (mg kg^{-1})	19.85
Exchangeable K (cmol (+) kg^{-1})	0.12
Available S (mg kg^{-1})	14.40

2.3. Experimental set up, crop establishment, management practices and crop harvest

The modern high yielding Zinc enriched BRRI dhan100 (Grain yield: 7.7 t ha^{-1}, growth duration: 148 d, amylose: 26.8% and grain Zn content: 25.7 mg kg^{-1}) was used in the experiment. This rice cultivar was developed for dry (Boro) season in 2021 by the Bangladesh Rice Research Institute (BRRI) from the cross between BR7166-5B-5/BG305/BRRI dhan29. Seeds of BRRI dhan100 were sown uniformly in well prepared wet nursery bed on December 11, 2021 (in first year) and December 07, 2022 (in second-year). In both years, seven treatments such as N_1=Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, resp. (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O$, resp.), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N_1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied) were tested. The experiment was laid out in Randomized Complete Block Design (RCBD) with three replicates and unit plot size of 3 m × 4 m. Full amount of P, K, S and Zn fertilizers were applied during final land preparation and thoroughly mixed with soil in six treatments (N_1, N_2, N_3, N_4, N_5 and N_6), except N_7. Except N_4 and N_7, urea was top dressed in all other five treatments into three equal splits on 15 days after transplanting (DAT), 30 DAT and 45 DAT, respectively in both experimental years. Cowdung was applied on 20 days before transplanting in both years, and 35 days old 2-3 seedlings $hill^{-1}$ were transplanted at 25 cm x 15 cm spacing on January 26 (2022) and January 13 (2023). Other standard management practices were followed for all treatments. Plant protection measures were followed as and when necessary.

The crop was harvested when approximately 85-90% of the grains had turned golden yellow, indicating physiological maturity. A central area of 6 m^2 from each plot was harvested to determine grain and straw yields. The harvested plants from each plot were bundled separately, properly labeled, and transported to the threshing floor. The bundles were sun-dried, threshed, and the grains were subsequently cleaned. Grain and straw weights along with their respective moisture contents, were recorded after adequate sun drying. Yields were then expressed in tons per hectare (t ha^{-1}) and adjusted to 14% and 3% moisture content for grain and straw, respectively. For calculating the yield attributes, six hills $plot^{-1}$ outside the sampling area were cut at ground level.

2.4. Analysis of plant samples

Collected grain and straw samples were analyzed for total N content by micro Kjeldahl method (Bremner and Mulvaney, 1982). Also di-acid (HNO3:HClO4 =3:1) digestion for grain and straw samples were performed to measure P concentrations calorimetrically using the molybdovanadate yellow color method (Yoshida et al.,1976), K concentration directly using a flame photometer (Yoshida et al., 1976) and S concentration by the turbidity method (Chaman and Pratt, 1964).

2.5. Calculation of N use efficiencies

Nitrogen use efficiencies were assessed using the following formulae.

Agronomic Efficiency of N (AE_N)

Agronomic efficiency of N (AEN) is the incremental efficiency of applied N reflecting how much additional yield was produced for each kg N applied (Dobermann & Fairhurst, 2000; Karmakar et al., 2021). Formula used for AE_N was:

$$AE_N\ (kg\ kg^{-1}) = \frac{(GY_{+N} - GY_{-N})}{FN} \quad \text{--------------- (1)}$$

Where, AE_N = Agronomic Efficiency of N, GY_{+N} = Grain yield (kg ha^{-1}) with N fertilizer application, GY_{-N}

= Grain yield (kg ha^{-1}) without N fertilizer application and FN = Amount of N fertilizer applied (kg ha^{-1}).

Physiological Efficiency of N (PE_N)

Physiological efficiency of N (PE_N) equates how much additional grain yield is produced for each additional kg of N uptake. PEN from applied N is the ratio of kg grain yield increase per kg N uptake (Dobermann and Fairhurst, 2000; Karmakar et al., 2021). The following formula was used:

$$PE_N\ (\text{kg kg}^{-1}) = \frac{(GY_{+N} - GY_{-N})}{(UN_{+N} - UN_{-N})} \quad \text{--------------- (2)}$$

Where, PE_N = Physiological efficiency of N; GY_{+N} = Grain yield (kg ha^{-1}) with N application; GY_{-N} = Grain yield (kg ha^{-1}) without N application; UN_{+N} = N uptake (kg ha^{-1}) from N fertilized plot and UN_{-N} = N uptake (kg ha^{-1}) from N unfertilized plot.

Internal Efficiency of N (IE_N)

Internal efficiency of N (IE_N) is the utilization efficiency of the N taken up by the crop indicating how much yield is produced per kg N taken up from both fertilizer and indigenous (soil) sources. The IEN is the ratio of kg grain per kg N taken up (Dobermann & Fairhurst, 2000; Karmakar et al., 2021). Formula for IE_N was:

$$IE_N\ (\text{kg kg}^{-1}) = \frac{GY}{UN} \quad \text{--------------- (3)}$$

Where, IE_N = Internal efficiency of N; GY = Grain yield (kg ha^{-1}) in N fertilized plot; UN = Total N uptake (kg ha^{-1}) in N fertilized plot from both indigenous soil and N fertilizer sources.

Nitrogen Harvest Index (NHI)

Nitrogen harvest index (NHI) is computed as the ratio of total grain N uptake and total plant N uptake. NHI was estimated using following formula (Fageria et al., 2010; Karmakar et al., 2021; Singh et al., 2014):

$$NHI = \frac{GN}{TN} \quad \text{--------------- (4)}$$

Where, NHI = Nitrogen harvest index, GN = Grain N uptake (kg ha^{-1}) and TN = Total plant N uptake (kg ha^{-1}).

2.6. Data Analysis

Data collected on yield, different parameters and N use efficiencies were analyzed using statistical software Statistix 10, and the least significant difference (LSD) test was performed according to Gomez and Gomez (1984).

3. Results and discussion

3.1. Variability in plant growth and yield contributing characters

Except 1000 grain weight, plant height, tiller production and other yield attributes were significantly ($p < 0.01$ to < 0.05) affected by different levels of N fertilizer application in both years (Table 2). Plant height of the treatments N_1, N_2, N_3, N_5 and N6 were statistically identical, which were again significantly higher than that in treatments N_4 and N_7 in both the experimental years Boro 2022 and 2023 (Table 2). Compared to N_4 and N_7, the plant height increased by 12.00-19.05 cm (in 2022 and 8.52–18.65 cm in 2023 across five N fertilizer applied treatments N1, N2, N3, N5 and N6. Enhanced N levels improved plant growth and development via stimulating numerous physiological processes like induced cell division and elongation with maximizing vegetative growth and plant height (Kumar et al., 2015; Timilsina et al., 2023). Nitrogen levels had significant effect (P = 0.01) on tiller production per unit area in both experimental years Boro 2022 and 2023 (Table 2). Significantly higher number of tillers per square meter were counted in the treatments N_2, N_5 and N_6, with its second higher values attained from N_1 and N_3 and the lowest values from N_4 and N_7 treatments in both years (Table 2). Number of tiller m^{-2} increased from 10 to 92 for different levels of N over no fertilizers which were equivalent to 4.50 to 41.44% increase in Boro 2022. Similar trends were also observed in Boro 2023 that corresponded to 1.73 to 38.96% increase. Panicle production of BRRI dhan100 was significantly affected by different nitrogen management options in both experimental years Boro 2022 and 2023 (Table 2). In Boro 2022, panicles m^{-2} were significantly greater in the treatments N_2, N_5 and N_6 ranging from 281 to 288 with their second higher values obtained from N_1 and N_3 (255 and 257, respectively). Accordingly, lower number of panicles m^{-2} were found in the without N treatments N_4 and N_7 (208 and 201, respectively). Hence, panicle production was higher in the treatments with N fertilizer applications than without N fertilizer applied treatments. Similar trends were also observed in Boro 2023. Rakotoson et al. (2017) found that panicles per square meter was consistently and positively correlated with N rates. These results were again in alignment with Karmakar et al. (2021) who reported that panicles production remarkably reduced with decreasing N rates. It was found that the panicle m^{-2} increased from 7-87 (equivalent to 3.4-43.28% increase in 2022) and 1-82 (equivalent to 0.48-39.05% increase in 2023) for different levels of N over no N fertilizer. Rajesh et al. (2017) reported that application of 120 kg N ha^{-1} recorded significantly higher values for morpho-physiological parameters. Irrespective of years, significantly longer panicles (25.38-27.34 cm) were measured in all five treatments with N fertilizer application compared to the treatments without N fertilizer application and no fertilizer application (21.06-22.32 cm) (Table 2). As the rate of N fertilizer increases, more nitrogen is contributed to the development, elongation, and length of the panicle (Islam et al., 2008). Number of grains panicle^{-1} varied from 73 to 112 across the treatments. Irrespective of years, significantly higher number of grains panicle^{-1} (100-112) were measured in all five treatments with N fertilizer application compared to the treatments without N fertilizer application and no fertilizer application (73-81) (Table 2). Number of grains panicle^{-1} increased by 1-34 in Boro 2022 and 8-9 in Boro 2023 across six treatments with different levels of nitrogen and no N over absolute control treatment. Similar results also reported by Dass et al. (2016) and Islam et al. (2008). Both the fertility and sterility percentage of BRRI dhan100 were significantly influenced by the treatments (Table 2). Moreover, grain fertility percentages were significantly greater in the treatments N_1, N_3, N_5 and N_6 in both years than other treatments. Thousand grain weight of BRRI dhan100 was not affected by nutrients/N rates (Table 2) which might be due to the fact that grain weight has been considered as one of the genetically controlled characteristics. These findings are in agreement with Karmakar et al. (2021) who reported that N rates had no significant effect on rice grain weight.

Table 2

Effect of different N level on growth and yield attributes of BRRI dhan100 during 2022 and 2023 dry (Boro) season rice at SAU Dhaka, Bangladesh.

Treatment	Plant height (cm)	Tillers m^{-2} (no.)	Panicles m^{-2} (no.)	Panicle length (cm)	Grains panicle^{-1} (no.)	Fertility (%)	Sterility (%)	1000-grain wt. (g)
				2022 Dry (Boro) Season				
N_1	97.45 ab	276 b	255 b	25.76 a	104 a	79.4 a	20.6 bc	16.98
N_2	101.76 a	309 a	285 a	25.45 a	101 a	75.4 b	24.6 a	16.42
N_3	98.03 ab	279 b	257 b	25.38 a	102 a	79.1 a	20.9 bc	16.43
N_4	85.45 bc	232 c	208 c	21.26 b	77 b	75.5 b	24.5 a	15.69
N_5	100.37 a	314 a	288 a	26.09 a	110 a	82.1 a	17.9 c	16.89
N_6	101.21 a	304 a	281 a	26.49 a	105 a	80.8 a	19.2 bc	16.64
N_7	82.71 c	222 c	201 c	21.06 b	76 b	73.1 b	26.9 a	15.58
$LSD_{(0.05)}$	13.63	24.53	21.18	2.372	10.13	3.961	2.092	--
F-test	0.05	0.01	0.05	0.01	0.01	0.05	0.01	NS
				2023 Dry (Boro) Season				
N_1	100.11 ab	272 b	250 b	25.68 a	106 a	79.7 ab	20.3 b	16.84
N_2	103.21 a	315 a	289 a	26.09 a	100 a	73.5 c	26.5 a	16.08
N_3	97.24 ab	290 ab	269 ab	25.42 a	105 a	80.8 ab	19.2 b	16.38
N_4	88.72 bc	235 c	211 c	22.32 b	81 b	78.4 b	20.6 b	15.86
N_5	100.19 ab	321 a	292 a	27.34 a	112 a	84.2 a	15.8 c	16.72
N_6	100.88 a	297 ab	275 ab	26.87 a	104 a	80.6 ab	19.4 b	16.70
N_7	84.56 c	231 c	210 c	21.70 b	73 b	71.6 c	28.4 a	15.25
$LSD_{(0.05)}$	10.94	36.75	26.32	2.690	13.45	4.051	3.561	--
F-test	0.05	0.01	0.01	0.01	0.01	0.01	0.01	NS

Means within a column with similar letter(s) were statistically identical, whereas different letter(s) differed significantly at $p < 0.01$ and $p < 0.05$.

N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, resp. (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O/7H_2O$, resp.), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N_1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied)

3.2. Variability in Grain, Straw, Biological yields, and Harvest Index

Grain, straw and biological yields, and harvest index of BRRI dhan100 were significantly ($p < 0.01$ to < 0.05) affected by the treatments in both the experimental years Boro 2022 and 2023 (Table 3). Mean grain yield of the treatments N_1, N_5 and N_6 were statistically similar and significantly higher ($p < 0.01$) than the other treatments. Grain yield of N_2 found lower than N_1 although 33% higher N was applied in N_2. This was likely due to lodging of the crop in the plots of treatments N_2 for excess N application. Grain yields were lower in the treatments where no or lower amount of N was applied. These findings were similar to those of Karmakar et al. (2021) who stated that grain yield decreased with application of excess N. These enhancements in grain yield in N_1, N_5 and N_6

may be resulted from balanced nitrogen application rates which stimulated dry matter accumulation, accelerated plant growth rate, promoted internode elongation and enhanced gibberellin activity (Ghoneim et al., 2018). Furthermore, the observed grain yields improvement in N_1, N_5 and N_6 than other N treatments could be associated with nitrogen's pivotal role in increasing the most striking yield components especially higher number of grains per panicle and fertility percent, and lower sterility percent (Table 2) matching with findings of Karmakar et al. (2021) and Gueye and Becker (2011). Straw yield was significantly ($p<0.01$) affected by different treatments in both years, Boro 2022 and 2023 (Table 3). Among the treatments, the highest straw yield (7.56 and 7.78 t ha^{-1} in Boro 2022 and 2023, respectively) in the treatment N_5 were due to the application of additional organic manure i.e. 5 t ha^{-1} cowdung that might be contributed to enhance vegetative growth as well as straw yield compared to the other treatments. The production of higher straw might be increased in N_5 due to application of additional N from 5 t ha^{-1} cowdung with 100% chemical N fertilizer. The results are in line with the findings of Karmakar et al. (2021) and Swain et al. (2006) who reported that increasing N rates increased rice straw yield. Biological yield (Grain + Straw) was statistically affected by the treatments and also follow the similar trend of straw yield as the treatment N_5 produced the highest biological yield. Moreover, it was statistically similar in the treatments N_1 and N_6. In general, biological yield was higher in the N applied treatments compared to without N fertilizer applied treatments. These results on biological yields mostly due to more straw yields in N_5, N_1 and N_6 with balanced and integrated N fertilizer applications compare to imbalanced (over or under N rates and absence) N fertilizer managements (Karmakar et al., 2021; Peng et al., 2006). Harvest index of BRRI dhan100 was significantly affected by the treatments (Table 3). In both years, harvest index was higher and statistically identical across N_1, N_4, N_5 and N_6 treatments. Harvest index was the lowest in N_7 (without fertilizers) that might be due to lower grain yield. While Rakotoson et al. (2017) found that harvest index was consistently positively correlated with N rates.

Table 3

Effect of different N levels on grain, straw, biological yields and harvest index of BRRI dhan100 during Boro 2022 and 2023 season at SAU Dhaka, Bangladesh.

Treatment	Grain yield ($t\ ha^{-1}$)	Straw yield ($t\ ha^{-1}$)	Biological yield ($t\ ha^{-1}$)	Harvest index (%)
		2022 Dry (Boro)Season		
N_1	6.36 a	6.76 b	13.12 b	48.48 a
N_2	5.56 b	6.83 b	12.38 c	44.91 ab
N_3	4.67 c	5.71 c	10.38 d	44.99 ab
N_4	4.13 c	4.62 d	8.75 e	47.20 a
N_5	6.76 a	7.56 a	14.32 a	47.21 a
N_6	6.39 a	6.91 b	13.30 b	48.05 a
N_7	3.46 d	4.59 d	8.06 e	42.93 b
$LSD_{(0.05)}$	0.587	0.534	0.696	2.781
F-test	0.01	0.01	0.01	0.05
		2023 Dry (Boro) Season		
N_1	6.57 a	6.87 b	13.45 b	48.85 a
N_2	5.63 b	6.91 b	12.54 b	44.90 b
N_3	4.74 c	5.86 c	10.60 c	44.72 b
N_4	4.34 c	4.74 d	9.09 d	47.74 a
N_5	6.83 a	7.78 a	14.62 a	46.72 ab
N_6	6.52 a	7.05 b	13.57 b	48.05 a
N_7	3.60 d	4.68 d	8.28 d	43.48 b
$LSD_{(0.05)}$	0.568	0.696	1.011	2.391
F-test	0.01	0.01	0.01	0.05

In a column means with similar letter(s) were statistically identical and those having dissimilar letter(s) differed significantly at $p<0.01$ and $p<0.05$.

N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, respectively (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O/7H_2O$, respectively), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N_1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied)

3.3. Nitrogen use efficiencies (NUE)

Nitrogen use efficiencies (NUE) such as Agronomic efficiency of N (AEN), Physiological efficiency of N (PEN), Internal efficiency of N (IEN) and Nitrogen harvest index (NHI) of BRRI dhan100 were significantly ($p<0.01$) affected by fertilizer management options (Table 4). Irrespective of year, significantly ($p<0.01$) higher agronomic N use efficiency, AEN (in kg grain kg^{-1} N applied) of BRRI dhan100 was recorded in N_1, N_5 and N_6 (21.63 to 23.98) treatments than that in N_2 (12.28 to 12.69) and N_3 (13.69 to 14.50) with 33% higher and lower N application rates, respectively. Ladha et al. (2005) reported AEN values of 22 kg kg^{-1} N for rice. The optimum use of nitrogen fertilizer had a significant effect on AEN. Moreover, Cai et al. (2022) reported that AEN was dominated by the ability of the plant to mobilize N rather than N uptake. Physiological efficiency of N (PEN) of BRRI dhan100 was statistically influenced by the treatments in both experimental years 2022 and 2023 Boro seasons (Table 4). Overall PEN ranged from 24.51 to 40.36 kg kg^{-1} among the treatments. These results were also parallel with the findings of Dobermann and Fairhurst (2000) who reported that PEN ranged from 22 to 49 kg kg^{-1} with an average of 35 kg kg^{-1}. In both years, significantly ($p<0.01$) higher PEN (about 40 kg kg^{-1}) was recorded in N_5, which was again statistically identical with that in N_1 (about 37 kg kg^{-1}) and N_6 (about 38 kg kg^{-1}) but differed from that in N_3 (~29 to 34 kg kg^{-1}) and N_2 (about 25 kg kg^{-1}). Yesuf and Balcha (2014) reported the PEN of 38 to 29 when N rate increased from 3.5 to 14 g m^{-2}, respectively. In both years, internal efficiency of N (IEN) of BRRI dhan100 was the highest in N_4 (273 and 310 kg kg^{-1}) followed by N_7 (242 and 257 kg kg^{-1}), while the lowest IEN (57 and 58 kg kg^{-1}) was found in N_2. Across the N fertilizer applied treatments, the sequence of IEN (kg kg^{-1}) was N_3 (88-89) $>N_1$, N_5 and N_6 (67-71), $>N_2$ (57-58) in two years. In both years, the IEN (kg kg^{-1}) in N_1, N_5 and N_6 were also statistically identical but greater than that in N_2 and lower than that in N_3. Chiranjeeb et al. (2022) reported that 50% N through urea + 50% N through vermicompost registered the highest internal efficiency of nitrogen (IRN). Irrespective of year, nitrogen harvest index (NHI) of BRRI dhan100 ranged from 0.43 to 0.55 kg kg^{-1} across the treatments having the highest ($p<0.01$) NHI (0.55 kg kg^{-1}) was recorded in N_2 (Table 4). The lowest NHI (0.41-0.43 kg kg^{-1}) was found in N_3 which was statistically identical with that in N_4 (0.44-0.46 kg kg^{-1}) and N_7 (0.43-0.45 kg kg^{-1}) (Table 4). Moreover, the second higher and statistically identical NHI was recorded across N_1, N_5 and N_6 treatments (0.47-0.50 kg kg^{-1}) in both years. The variations in NHI are related with the capacity of rice genotype to utilize N and N levels for growth and development (Swain et al., 2006 and Singh et al., 1998). Our results corroborated with findings of Swain et al. (2006) and Karmakar et al. (2021) who found that the NHI ranged from 0.45 to 0.69 kg kg^{-1} and 0.52 to 0.58 kg kg^{-1}, respectively.

Table 4

Treatments effect on different N use efficiency of BRRI dhan100 during Boro 2022 and 2023 growing season at SAU Dhaka, Bangladesh.

Treatments	AE_N (kg kg^{-1})	PE_N (kg kg^{-1})	IE_N (kg kg^{-1})	NHI (kg kg^{-1})
		2022 Dry (Boro) Season		
N_1	22.72 a	36.99 ab	67 d	0.48 b
N_2	12.69 b	25.42 c	57 e	0.55 a
N_3	14.50 b	33.90 b	88 c	0.43 c
N_4	0.00 c	0.00 d	273 a	0.44 c
N_5	23.55 a	40.36 a	70 d	0.50 b
N_6	21.68 a	38.01 ab	69 d	0.49 b
N_7	0.00 c	0.00 d	242 b	0.43 c
$LSD_{(0.05)}$	3.280	5.848	9.17	0.041
F-test	0.01	0.01	0.01	0.01
		2023 Dry (Boro) Season		
N_1	23.98 a	37.26 a	70 d	0.47 bc
N_2	12.28 b	24.51 c	58 e	0.55 a
N_3	13.69 b	29.31 b	89 c	0.41 c
N_4	0.00 c	0.00 d	310 a	0.46 bc
N_5	23.09 a	40.09 a	71 d	0.50 b
N_6	21.63 a	38.21 a	71 d	0.49 b
N_7	0.00 c	0.00 d	257 b	0.45 bc
$LSD_{(0.05)}$	3.454	3.846	11.78	0.038
F-test	0.01	0.01	0.01	0.01

Means within a column having similar letter(s) are statistically similar, whereas those with different letter(s) differ significantly at $p<0.01$.

AEN = Agronomic efficiency of N, PEN = Physiological efficiency of N, IEN = Internal efficiency of N and NHI = Nitrogen harvest index.

N_1 = Researcher's Practice (RP): N-P-K-S-Zn @ 124-22-75-20-4 kg ha^{-1}, resp. (equalling 270-112-150-112-11 kg ha^{-1} Urea-TSP-MoP-Gypsum-$ZnSO_4.H_2O/7H_2O$, resp.), N_2 = N_1 + 33% more N over N_1, N_3 = N_1- 33% less N than N_1, N_4 = N1 but no N was applied (-N), N_5 = N_1 + Cowdung@5 t ha^{-1}, N_6 = Soil test based (STB) N-P-K-S-Zn @ 130-20-83-21-3 kg ha^{-1}, respectively and N_7 = Absolute control (No fertilizers applied).

4. Conclusion

Grain yield, yield attributes, different nitrogen use efficiency and overall performances of BRRI dhan100 had significantly affected by integrated nutrient management (N_5) as well as soil test based (STB: N_6) and Researcher's Recommended (N_1) N fertilizer management options. Among the treatment combinations, N_1 (Researcher's Practice: N-P-K-S- Zn @ 124-22-75-20-4 kg ha^{-1}), N_5: N_1 + Cowdung @5 t ha^{-1} and N_6 (Soil test-based dose: N-P-K-S-Zn @ 130-24-83-22-3 kg ha^{-1}) treatments consistently provided the higher potentiality in plant growth, yield attributes, yield and nitrogen use efficiencies of BRRI dhan100. Consequently, the treatment N_1, N_5 and N_6 may be recommended for BRRI dhan100 to achieve higher yield, improve N use efficiencies and ensure food security of the country. Further verifications by long-term experiments with studying changes in postharvest soil properties will provide detailed insights for sustainable soil health management.

Authors' contribution

CMHK and BK conceived the idea and carried out the experiments and data collection, drafting of manuscript. BK, MMH and AKP edited, interpretated and improved the manuscript. All authors read and approved the final manuscript.

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Competing interest

The authors declare that they have no competing interests.

References

Akter, M., Islam, S. M. M., Islam, M. N., Rahman, M. S., Islam, A., Khanam, M., Iqbal, M., & Islam, M. R. (2024). Optimizing Rice Yield and Nutrient Uptake: Investigating the Interaction Between Nitrogen and Potassium in Wet Season Rice Cultivation. Advances in Agriculture, 2024(1), 4984165. https://doi.org/10.1155/aia/4984165.

Anas, M., Liao, F., Verma, K. K., Sarwar, M. A., Mahmood, A., Chen, Z.-L., Li, Q., Zeng, X.-P., Liu, Y., & Li, Y.-R. (2020). Fate of nitrogen in agriculture and environment: Agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. Biological Research, 53(1), 47. https://doi.org/10.1186/s40659-020-00312-4.

Azimi, S., Kaur, T., & Gandhi, T. K. (2021). A deep learning approach to measure stress level in plants due to Nitrogen deficiency. Measurement, 173, 108650. https://doi.org/10.1016/j.measurement.2020.10865.

Bangladesh Meteorological Department. (2024). Weather data. Retrieved October 3, 2025, from https://live6.bmd.gov.bd/

Bangladesh Rice Knowledge Bank. (n.d.). Retrieved October 12, 2024, from https://knowledgebank-brri.org/.

Bremner, J. m., & Mulvaney, C. S. (1982). Nitrogen-Total. In Methods of Soil Analysis (pp. 595–624). John Wiley & Sons, Ltd. https://doi.org/10.2134/agronmonogr9.2.2ed.c3

Cai, S., Zhao, X., & Yan, X. (2022). Effects of climate and soil properties on regional differences in nitrogen use efficiency and reactive nitrogen losses in rice. Environmental Research Letters, 17. https://doi.org/10.1088/1748-9326/ac6a6b.

Cameron, K. C., Di, H. j., & Moir, J. l. (2013). Nitrogen losses from the soil/plant system: A review. Annals of Applied Biology, 162(2), 145–173. https://doi.org/10.1111/ aab.12014.

Catalogue_2014.pdf. (n.d.). Retrieved September 7, 2025, from http://books.irri.org/catalogue_2014.pdf.

Chiranjeeb, K., Prasad, S, Kumar, V., K., R., Majhi, M., & Bhadani, M. (2022). Effect of vermicompost and fertilizer on uptake and efficiency of nutrients in pot culture rice. Environment Conservation Journal, 23, 295–302. https://doi.org/10.36953/ECJ.10052224.

Dass, A., Chandra, S., Choudhary, A. K., Singh, G., & Sudhishri, S. (2016). Influence of field re-ponding pattern and plant spacing on rice root–shoot characteristics, yield, and water productivity of two modern cultivars under SRI management in Indian Mollisols. Paddy and Water Environment, 14(1), 45–59. https://doi.org/10.1007/s10333-015-0477-z.

Demir, Z., Keçeci, M., & Tunç, A. E. (2021). Effects of nitrogen fertigation on yield, quality components, water use efficiency and nitrogen use efficiency of silage maize (*Zea Mays* L.) as the second crop. Journal of Plant Nutrition, 44(3), 373–394. https://doi.org/10.1080/01904167.2020.182239.

Dobermann, A., & Fairhurst, T. H. (2000). Nutrient disorders and nutrient management. Potash and Phosphate Institute, Potash and Phosphate Institute of Canada and International Rice Research Institute, Singapore, 191.

Dobermann, A. R. (2005). Nitrogen use efficiency – state of the art. department of agronomy and horticulture: Faculty Publications. https://digitalcommons.unl.edu/agronomyfacpub/316.

Fageria, N. K., Santos A. B. D., & Cutrim V. D. A. (2009). Nitrogen uptake and its association with grain yield in lowland rice genotypes. J. Plant Nutr. 32 (11), 1965-1974.

Fageria, N. K., De Morais, O. P., & Dos Santos, A. B. (2010). Nitrogen use efficiency in upland rice genotypes. Journal of Plant Nutrition, 33(11), 1696–1711. https://doi.org/10.1080/01904167.2010.496892

Fageria, N. K. (2014). Nitrogen management in crop production. CRC Press. https://doi.org/10.1201/b17101.

Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W. J., & Zhang, F. (2012). Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. Journal of Experimental Botany, 63(1), 13–24. https://doi.org/10.1093/jxb/err248.

FRG (2024) Fertilizer Recommendation Guide. Bangladesh Agricultural Research Council. - References—Scientific Research Publishing. (n.d.). Retrieved September 7, 2025, from https://www.scirp.org/reference/referencespaper?referenceid=3969710.

Gao, Q., Li, C., Feng, G., Wang, J., Cui, Z., Chen, X., & Zhang, F. (2012). Understanding yield response to nitrogen to achieve high yield and high nitrogen use efficiency in rainfed corn. Agronomy Journal, 104(1), 165–168. https://doi.org/10.2134/agronj2011.0215.

Gueye, T. & Becker, H. (2011). Genetic variation in nitrogen efficiency among cultivars of irrigated rice in Senegal. J. Agric. Biotech. Sust. Dev. 3, 35–43.

Ghoneim, A. M., E.E., G., & Osman, M. M. A. (2018). Effects of Nitrogen Levels on Growth, Yield And Nitrogen use Efficiency Of Some Newly Released Egyptian Rice Genotypes. Open Agriculture, 3(1), 310–318. https://doi.org/10.1515/opag-2018-0034.

Gomez, K. A., & Gomez, A. A. (1984). Statistical procedures for agricultural research. John wiley & sons.

Gondwal, P., Rana, M., Dhankar, A., S., & Mohan, J. (2024). Role of nano-urea in optimizing nitrogen use efficiency, yield and quality of rice: A review. International Journal of Research in Agronomy, 7(10S), 182–187. https://doi.org/10.33545/2618060X.2024.v7.i10Sc.1724..

Haefele, S. M., Jabbar, S. M. A., Siopongco, J. D. L. C., Tirol-Padre, A., Amarante, S. T., Sta Cruz, P. C., & Cosico, W. C. (2008). Nitrogen use efficiency in selected rice (*Oryza sativa* L.) genotypes under different water regimes and nitrogen levels. Field Crops Research, 107(2), 137–146. https://doi.org/10.1016/j.fcr.2008.01.007

Hameed, F., Xu, J., Rahim, S. F., Wei, Q., Rehman Khalil, A. ur, & Liao, Q. (2019). Optimizing nitrogen options for improving nitrogen use efficiency of rice under different water regimes. Agronomy, 9(1), 39. https://doi.org/10.3390/agronomy9010039.

Hu, A., Tang, T., & Liu, Q. (2018). Nitrogen use efficiency in different rice-based rotations in southern China. Nutrient Cycling in Agroecosystems, 112(1), 75–86. https://doi.org/10.1007/s10705-018-9930-x.

Islam, M. S., Akhter, M. M., Rahman, M. S., Banu, M. B., & Khalequzzaman, K. M. (2008). Effect of nitrogen and number of seedlings per hill on the yield and yield components of T. aman rice (BRRI Dhan 33). https://ggfjournals.com/assets/uploads/61-651.pdf.

Islam, S. M. M., Gaihre, Y. K., Shah, A, L., Singh, U., Sarkar, M. I. U., Satter, M. A., Sanabria, J., & Biswas, J. C. (2016). Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh. Nutrient Cycling in Agroecosystems, 106. https://doi.org/10.1007/s10705-016-9795-9.

Jahan, A., Islam, A., Sarkar, M. I. U., Iqbal, M., Ahmed, M. N., & Islam, M. R. (2022). Nitrogen response of two high yielding rice varieties as influenced by nitrogen levels and growing seasons. Geology, Ecology, and Landscapes, 6(1), 24–31. https://doi.org/10.1080/24749508.2020.1742509.

Jahan, S., Sarkar, M., & Paul, S. (2017). Variations of growth parameters in transplanted Aman rice (cv. BRRI dhan39) in response to plant spacing and fertilizer management. Archives of Agriculture and Environmental Science, 2(1), 1-5. Retrieved from https://journals.aesacademy.org/index.php/aaes/article/view/02-01-01. Jayara, A. S., Kumar, R., Pandey, P., Singh, S., Shukla, A., Singh, A. P., Pandey, S., Meena, R. L., & Reddy, K. I. (2023). Boosting nutrient use efficiency through fertilizer use management. Applied Ecology and Environmental Research, 21(4), 2931–2952. https://doi.org/10.15666/aeer/2104_29312952.

Jones, C., Brown, B.D., Engel, R., Horneck, D. and Olson-Kurtz, K. (2013). Factors Affecting Nitrogen Fertilizers Volatilization. Montana State University

Extension, United States Department of Agriculture, Bozeman, MT, EB0208, 1-5. - References—Scientific Research Publishing. (n.d.). Retrieved September 7, 2025, from https://www.scirp.org/reference/referencespapers?referenceid=2034302.

Kader, M. A., Sleutel, S., Begum, S. A., Moslehuddin, A. Z. M., & De neve, S. (2013). Nitrogen mineralization in sub-tropical paddy soils in relation to soil mineralogy, management, pH, carbon, nitrogen and iron contents. European Journal of Soil Science, 64(1), 47–57. https://doi.org/10.1111/ejss.12005.

Kader, M. A., Yeasmin, S., Solaiman, Z. M., De Neve, S., & Sleutel, S. (2017). Response of hydrolytic enzyme activities and nitrogen mineralization to fertilizer and organic matter application in subtropical paddy soils. European Journal of Soil Biology, 80, 27–34. https://doi.org/10.1016/j.ejsobi.2017.03.004.

Karmakar, B., Ahmed, B., Biswash, M., & Hasan, M. M. (2020). Adaptation of Promising Rice Genotypes for Transplant Aus Season. Bangladesh Rice Journal 23 (2) : 35-48, 2019, doi.org/10.3329/brj.v23i2.48246.

Karmakar, B., Haefele, S. M., Henry, A., Kabir, M. H., Islam, A., & Biswas, J. C. (2021). In quest of nitrogen use-efficient rice genotypes for drought-prone rainfed ecosystems. Frontiers in Agronomy, 2. https://doi.org/10.3389/fagro.2020.607792.

Knobeloch, L., Salna, B., Hogan, A., Postle, J., & Anderson, H. (2000). Blue babies and nitrate-contaminated well water. Environmental Health Perspectives, 108(7), 675–678. https://doi.org/10.1289/ehp.00108675.

Kumar, R., Goswami, S., Sharma, S., Kala, Y., Rai, G., Mishra, D., Grover, M., Singh, G., Pathak, D. S., Rai, A., Chinnusamy, V., & Rai, R. (2015). Harnessing next generation sequencing in climate change: RNA-Seq Analysis of Heat Stress-Responsive Genes in Wheat (Triticum aestivum L.). Omics : A Journal of Integrative Biology, 19. https://doi.org/10.1089/omi.2015.0097.

Ladha, J.K, HJ Pathak, T Krupnik, J Six and VC Kessel. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospect and prospects. Adv. Agron. 87, 85–156.

Liang, H., Gao, S., Ma, J., Zhang, T., Wang, T., Zhang, S., & Wu, Z. (2021). Effect of nitrogen application rates on the nitrogen utilization, yield and quality of rice. Food and Nutrition Sciences, 12(1), 13–27. https://doi.org/10.4236/fns.2021.121002.

Lü, H., Liang, W., Wang, G., Connor, D. J., & Rimmington, G. M. (2009). A simulation model assisted study on water and nitrogen dynamics and their effects on crop performance in the wheat-maize system: (II) model calibration, evaluation and simulated experimentation. Frontiers of Agriculture in China, 3(2), 109–121. https://doi.org/10.1007/s11703-009-0025-y.

Luo, J., Pan, Y.-B., Que, Y., Zhang, H., Grisham, M. P., & Xu, L. (2015). Biplot evaluation of test environments and identification of mega-environment for sugarcane cultivars in China. Scientific Reports, 5(1), 15505.

Ma, T., Chen, K., He, P., Dai, Y., Yin, Y., Peng, S., Ding, J., Yu, S., & Huang, J. (2022). Sunflower photosynthetic characteristics, nitrogen uptake, and nitrogen use efficiency under different soil salinity and nitrogen applications. Water, 14(6), 982. https://doi.org/10.3390/w14060982.

Mahajan, G., Sekhon, N. K., Singh, N., Kaur, R., & Sidhu, A. S. (2010). Yield and nitrogen-use efficiency of aromatic rice cultivars in response to nitrogen fertilizer. Journal of New Seeds, 11(4), 356–368. https://doi.org/10.1080/1522886X.2010.520145.

Mahbub, M., Bhuiyan, K., & Kabir, M. (2017). Performance of metsulfuron methyl 10% + chlorimuron ethyl 2% wp against annual weed inhibition in transplanted rice. https://doi.org/10.21276/haya.2017.2.8.3.

Mahender, A., Anandan, A., Pradhan, S. K., & Pandit, E. (2016). Rice grain nutritional traits and their enhancement using relevant genes and QTLs through advanced approaches. SpringerPlus, 5(1), 2086. https://doi.org/10.1186/s40064-016-3744-6.

Meena, V. S., Maurya, B. R., & Verma, J. P. (2014). Does a rhizospheric microorganism enhance $K+$ availability in agricultural soils? Microbiological Research, 169(5), 337–347. https://doi.org/10.1016/j.micres.2013.09.003.

Meisinger, J. J., Schepers, J. S., & Raun, W. R. (2008). Crop nitrogen requirement and fertilization. in nitrogen in agricultural systems (pp. 563–612). John Wiley & Sons, Ltd. https://doi.org/10.2134/agronmonogr49.c14.

Mitra, G. (2017). Essential plant nutrients and recent concepts about their uptake. In M. Naeem, A. A. Ansari, & S. S. Gill (Eds.), Essential Plant Nutrients: Uptake, Use Efficiency, and Management (pp. 3–36). Springer International Publishing. https://doi.org/10.1007/978-3-319-58841-4_1.

Noor, M. A. (2017). Nitrogen management and regulation for optimum NUE in maize – A mini review. Cogent Food & Agriculture, 3(1), 1348214. https://doi.org/10.1080/23311932.2017.134821.

Peng, S., Tang, Q., & Zou, Y. (2009). Current status and challenges of rice production in china. Plant Production Science, 12(1), 3–8. https://doi.org/10.1626/pps.12.3.

Piper, C.S. (1966) Soil and plant analysis. hans publishers, bombay. - references-scientific research publishing. (n.d.). Retrieved September 7, 2025, from https://www.scirp.org/reference/referencespapers?referenceid=2430186.

Rajesh, K., Thatikunta, R., Naik, D. S., & Arunakumari, J. (2017). Effect of different nitrogen levels on morpho physiological and yield parameters in rice (*Oryza sativa* L.). Int. J. Curr. App. Sci, 6(8), 2227–2240.

Rakotoson, T., Dusserre, J., Letourmy, P., Ramonta, I. R., Cao, T.-V., Ramanantsoanirina, A., Roumet, P., Ahmadi, N., & Raboin, L.-M. (2017). Genetic variability of nitrogen use efficiency in rainfed upland rice. Field Crops Research, 213, 194–203.

Rezaei, M., Vahed, H., Amiri, E., Motamed, M. K., & Azarpour, E. (2009). The effects of irrigation and nitrogen management on yield and water productivity of rice. World Applied Sciences Journal.

Saha, P. K., Islam, S. M. M., Akter, M., & Zaman, S. K. (2012). Nitrogen response behaviour of developed promising lines of T.aman rice. Bangladesh Journal of Agricultural Research, 37(2), 207–213. https://doi.org/10.3329/bjar.v37i2.11222.

Singh, U, J K Ladha, EG Castillo, G Punzalan, A Tirol-Padre and M Duqueza. (1998). Genotypic variation in nitrogen use efficiency in medium-and long-duration rice. Field Crops Res. 58, 35-53.

Singh, H., Verma, A., Ansari, M. W., & Shukla, A. (2014). Physiological response of rice (Oryza sativa L.) genotypes to elevated nitrogen applied under field conditions. Plant Signaling & Behavior, 9(7), e29015. https://doi.org/10.4161/psb.29015.

Statistical-Yearbook-of-Bangladesh-2019.pdf. (n.d.). Retrieved September 7, 2025, from https://bcpabd.com/wp-content/uploads/2021/04/Statistical-Yearbook-of-Bangladesh-2019.pdf?utm_source=chatgpt.com.

Swain, D. K., Bhaskar B. C., Krishnan P., Rao K. S., Nayak S. K. & Dash R. N. 2006. Variation in yield, N uptake and N use efficiency of medium and late duration rice varieties. J. Agril. Sci. 144, 69–83.

Tao, H., Morris, T. F., Kyveryga, P., & McGuire, J. (2018). Factors affecting nitrogen availability and variability in cornfields. Agronomy Journal, 110(5), 1974–1986. https://doi.org/10.2134/agronj2017.11.0631.

Thorburn, P. J., Biggs, J. S., Palmer, J., Meier, E. A., Verburg, K., & Skocaj, D. M. (2017). Prioritizing crop management to increase nitrogen use efficiency in australian sugarcane crops. Frontiers in Plant Science, 8. https://doi.org/10.3389/fpls.2017.01504.

Timilsina, S., & Vista, S. (2022). Nitrogen Use Efficiency (Nue) And Rice Productivity As Affected By Different Levels Of Nitrogen Application In Hill Conditions Of Nepal. Tropical Agrobiodiversity, 3, 29–33. https://doi.org/10.26480/trab.02.2022.29.33.

Wang, R. M,, Chen, C. C., Yang, X. E. and Zhang, Y. X. (2009). Growth Responses to Varying Zinc Activities in Rice Genotypes Differing in Zn Efficiency and Zn Density. Journal of Plant Nutrition, 32:4, 681-693 To link to this article: http://dx.doi.org/10.1080/ 01904160902734950.

Wasaya, A., Yasir, T. A., Sarwar, N., Atique-ur-Rehman, Mubeen, K., Rajendran, K., Hadifa, A., & Sabagh, A. E. L. (2022). Climate change and global rice security. In N. Sarwar, Atique-ur-Rehman, S. Ahmad, & M. Hasanuzzaman (Eds.), Modern Techniques of Rice Crop Production (pp. 13–26). Springer. https://doi.org/10.1007/978-981-16-4955-4_2.

World Food and Agriculture – Statistical Yearbook 2022. (n.d.). Retrieved September 8, 2025, from https://openknowledge.fao.org/items/ffc06bd1-b7e9-4b94-a6a7-9ba45352976b.

World Food and Agriculture – Statistical Yearbook 2023. (2023). FAO. https://doi.org/10.4060/cc8166en.

Wu, L., Yuan, S., Huang, L., Sun, F., Zhu, G., Li, G., Fahad, S., Peng, S. & Wang. F. (2016). Physiological mechanisms underlying the high-grain yield and high-nitrogen use efficiency of elite rice varieties under a low rate of nitrogen application in China. Front. Plant Sci. 7, 1024.

Yesuf, E., & Balcha, A. (2014). Effect of nitrogen application on grain yield and nitrogen efficiency of rice (*Oryza sativa* L.). https://www.cabidigitallibrary.org/doi/full/10.5555/20143310104.

Zhao, L., Wu, L., Dong, C. & Yu Li. (2010). Rice yield, nitrogen utilization and ammonia volatilization as influenced by modified rice cultivation at varying nitrogen rates. Agricultural Sciences, 01(01), 10–16. https://doi.org/10.4236/as.2010.11002.

Zhao, S.P., Zhao, X. Q. & Shi, W. M. (2012). Genotype variation in grain yield response to basal N fertilizer supply among different rice cultivars. African J. Biotech. 11(59), 12298-12304.

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Optimizing Transplanting Time to Mitigate High Temperature Stress and Maximize Yield in Boro Rice Varieties in Barishal Region of Bangladesh

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ABSTRACT

Rice yield is highly sensitive to environmental conditions, particularly planting time and temperature. Since rice varieties differ in their tolerance to high-temperature stress, identifying an appropriate transplanting window is essential for ensuring proper tillering, flowering, grain formation, and overall yield. This study examined how high-temperature stress, modulated by different transplanting dates, affects the yield attributes and grain yield of three Boro rice varieties in Barishal. The field experiment was carried out during the 2023–2024 Boro (dry) season at the Sagardi farm of the Bangladesh Rice Research Institute (BRRI), Regional Station, Barishal. The experiment was laid out in a split-plot design with three replications. Six transplanting dates (10 December, 25 December, 10 January, 25 January, 10 February, and 25 February) and three rice varieties (BRRI dhan89, BRRI dhan92, and BRRI dhan102) were evaluated. All three varieties performed best when transplanted on 25 December, producing the highest grain yields: BRRI dhan89 (7233.49 kg ha^{-1}), BRRI dhan92 (7477.91 kg/ha), and BRRI dhan102 (8097.82 kg/ha). These peak yields were accompanied by maximum tiller and panicle production, higher grain numbers per panicle, and greater thousand-grain weight. Conversely, transplanting on 25th February led to the highest spikelet sterility, while 25 December showed the lowest, highlighting the strong influence of temperature during reproductive stages. Based on these findings, farmers in the Barishal region are advised to transplant Boro rice seedlings between 10th December and 10th January to achieve optimum yield and minimize high temperature-induced sterility. Future research should include a broader range of high-yielding varieties and evaluate similar transplanting schedules across diverse rice-growing regions of Bangladesh to strengthen region-specific recommendations.

1. Introduction

Rice (*Oryza sativa* L.) is one of the world's most essential staple foods, sustaining nearly two-thirds of the global population. Beyond its nutritional value, rice is deeply woven into the cultural identity, economic stability, and daily lives of millions across Asia and other regions (Harbinson et al., 2021). As the

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global population continues to rise, the demand for food is expected to reach 14,886 million tons (MT) by 2050, necessitating substantial increases in agricultural production to maintain global food security (Islam et al., 2019).

Currently, global rice production stands at about 503.17 MT, with major contributions from China, India, and Bangladesh, underscoring the crop's worldwide significance (USDA, 2020). In Bangladesh in particular, rice is central to national food security, rural livelihoods, and socioeconomic stability (Jamal et al., 2023). However, rapid population growth, shrinking cultivable land, and the increasing impacts of climate variability place immense pressure on rice production systems. This makes the adoption of effective agronomic strategies more urgent than ever.

Among the available strategies, optimizing the timing of sowing and transplanting plays a pivotal role in achieving high yields. Ideal transplanting time is influenced by soil temperature, weather patterns, varietal characteristics, and regional agroecological conditions (Deshmukh and Patel, 2013; Yoshida and Parao, 1976). Rice requires specific temperature ranges to successfully complete critical growth stages such as panicle initiation, flowering, and grain filling. When transplanting is done at the appropriate time, plants can grow uniformly and benefit from favorable environmental conditions that enhance their development (Vange and Obi, 2006).

Delayed transplanting, however, often shortens the vegetative growth phase, reduces tillering capacity, and ultimately results in lower yields. Selecting the correct transplanting window is therefore essential, as it ensures the accumulation of adequate heat units required for proper plant growth and development (Rani and Maragatham, 2013). Because rice varieties vary in their growth duration, photosensitivity, temperature tolerance, and vegetative lag, the decision regarding when to transplant becomes even more critical. Timely transplanting not only supports vigorous vegetative growth but also helps avoid cold or heat stress during the sensitive reproductive stage, improving grain filling and grain quality (Farrell et al., 2003).

Heat stress (HS) has emerged as one of the most significant abiotic challenges threatening rice productivity. Elevated temperatures can disrupt physiological and morphological processes, increase spikelet sterility, and lead to severe yield losses, particularly when heat coincides with flowering (Shrestha et al., 2022). Studies suggest that rice yield may decline by up to 10% for every 1°C increase in temperature during critical stages of growth (Yang et al., 2017; Peng et al., 2004). As a result, adjusting transplanting dates to avoid periods of high-temperature stress is a critical component during the maturity stages of climate-smart rice cultivation, especially in the Barishal region of Bangladesh (Reddy and Narayana, 1984).

Earlier research has demonstrated that early transplanting can enhance dry matter accumulation, improve physiological efficiency, and increase grain yield compared to late transplanting (Khalifa, 2009; Mukesh et al., 2013). Across diverse environments, planting time consistently emerges as one of the most influential factors shaping rice productivity.

Considering these challenges and opportunities, the present study aims to evaluate the grain yield performance of newly developed long-duration Boro rice varieties across multiple transplanting dates in the Barishal Region of Bangladesh. By aligning varietal responses with temperature variations during the Boro season, this research seeks to identify an optimal transplanting window that minimizes high temperature stress and maximizes productivity for farmers in the region.

2. Materials and methods

2.1. Experimental materials

This experiment was conducted during the Boro season of 2023–2024 to evaluate how different transplanting dates influence the performance of selected Boro rice varieties under progressively delayed planting situations. Three modern, long-duration varieties-BRRI dhan89 (V1), BRRI dhan92 (V2), and BRRI dhan102 (V3)-were used as subplot factors. Six transplanting dates served as the main plot factors: 10 December (D1), 25 December (D2), 10 January (D3), 25 January (D4), 10 February (D5), and 25 February (D6).

All three varieties are suitable for irrigated transplanted cultivation in the Barishal region and are widely recommended for their stable performance under Boro season conditions. Their desirable characteristics are summarized in Table 1.

Table 1
Desirable features of the rice varieties used in the study.

Rice Variety	Yield (t/ha)	Growth Duration (days)	Other Desirable Features
BRRI dhan89	8.0	156	Medium-bold white grains; lifecycle 3–5 days shorter than BRRI dhan29
BRRI dhan92	8.4	156–160	Long slender white grains; requires less water for cultivation
BRRI dhan102	8.1	150	Long slender grains enriched with high zinc content

Source: BRRI (2025), Modern Rice Cultivation, 25th Edition, pp. 14–27.

2.2. Experimental site and design

The experiment was conducted at the Sagardi Farm of the Bangladesh Rice Research Institute (BRRI), Regional Station, Barishal (22.68034° N, 90.357486° E; elevation 2 m), during November 2023–June 2024. Initial soil samples were collected and analyzed at the Soil Resources Development Institute (SRDI), Divisional Laboratory, Barishal. The soil properties of the experimental field are presented in Table 2.

A split-plot design with three replications was used. Each block consisted of six main plots (transplanting dates), and each main plot contained three subplots (varieties), resulting in 54 treatment combinations (6 transplanting dates × 3 varieties × 3 replications).

Seedlings were raised in traditional seedbeds and, at 40 days of age, transplanted into well-prepared, puddled plots according to the treatment layout, with 2-3 seedlings planted per hill. Plant spacing was maintained at 20 cm × 20 cm. Fertilizers were applied at a rate of 170-15-75-17-2 kg ha^{-1} of N-P-K-S-Zn using urea, triple superphosphate, muriate of potash, gypsum, and zinc sulfate. All P, K, S, and Zn were applied as basal doses during final land preparation, while urea was top-dressed in three equal splits at 15, 35, and 50 days after transplanting (DAT).

Intercultural operations, including weeding, irrigation, and pest management, were performed as needed. The first weeding was carried out at 15 DAT and subsequently at 15–20 days intervals. Irrigation was maintained until the hard dough stage, after which plots were allowed to naturally drain during ripening. Daily maximum and minimum air temperatures were recorded using standard manual thermometers (Fig. 1).

2.3. Observations on yield and related traits

The number of tillers and panicles per hill was recorded at the maximum tillering and maturity stages, respectively. To estimate panicles per m^2, twenty-five hills were randomly sampled from each plot. Filled and unfilled grains were counted from five representative panicles per plot.

Grain yield was determined by harvesting a 5 m^2 area from the center of each plot (avoiding border effects) once more than 80% of grains had matured. Harvested grains were sun-dried, weighed, and adjusted to 14% moisture content before converting to kg ha^{-1}.

2.4. Growing degree days (GDD) calculation

To assess accumulated heat units during the crop growth period, Growing Degree Days (GDD) were calculated using the following formula (Liu et al., 2022):

$$GDD = \Sigma \left(\frac{Tmax + Tmin}{2} - Tbase \right)$$

Where:

Tmax = Maximum daily temperature (°C)
Tmin = Minimum daily temperature (°C)
Tbase = Base temperature below which rice growth ceases (10°C)

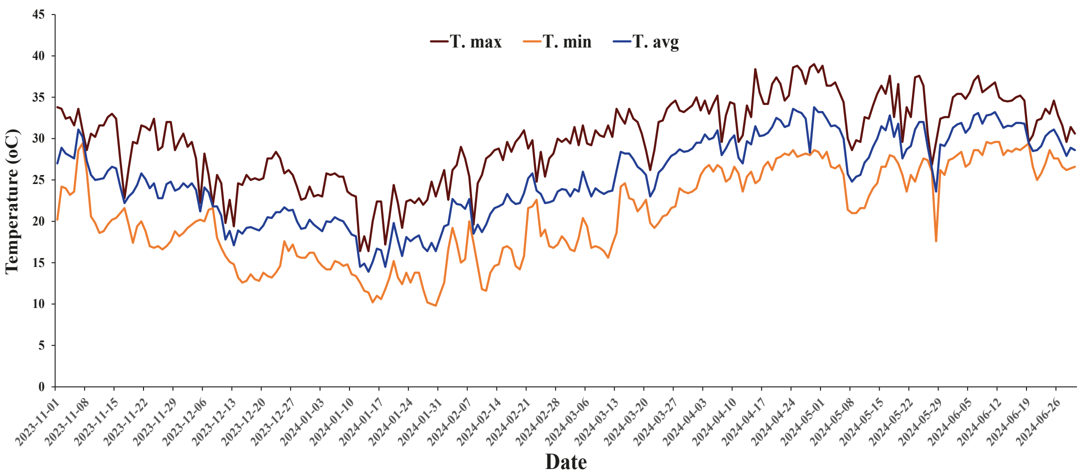

Fig. 1. Maximum, minimum and average air temperature during Boro 2023-24 season (Nov. 2023 – June 2024) at Sagardi Farm, BRRI Regional Station, Barishal.

2.5. Heat use efficiency (HUE) calculation

Heat Use Efficiency (HUE) was computed to evaluate how efficiently accumulated heat contributed to grain production (Gurleen et al. 2025):

$$HUE = \frac{(Grain\ Yield\ (kg/ha))}{CGDD}$$

Where:
CGDD = Cumulative Growing Degree Days from sowing to maturity

Soil Characteristics of the Experimental Site

Table 2
Soil characteristics of the study area, Sagardi Farm, BRRI, Regional Station, Barishal.

Soil Characteristics	Quantity
Texture	Clay
pH	7.1
Electrical Conductivity (dS/m)	1.41
Organic Matter (%)	2.32
Total Nitrogen (%)	0.116
Phosphorus (μg/g)	14.4
Potassium (meq/100g)	0.26
Sulfur (μg/g)	10.1
Zinc (μg/g)	1.97

Note: Soil characteristics were evaluated following the standard methods (Khan et al. 2009).

2.6. Statistical analysis

All data were analyzed using the Statistical Tool for Agricultural Research (STAR version 2.0.1, 2014), developed by the International Rice Research Institute (IRRI). Treatment means were compared using Duncan's Multiple Range Test (DMRT) (Gomez and Gomez, 1984) at appropriate significance levels to identify statistically meaningful differences among transplanting dates and rice varieties.

3. Results and discussion

3.1. Total tillers and panicles per hill

Transplanting time had a significant effect on the total number of tillers per hill (Fig. 2). All three varieties produced the highest number of tillers when transplanted on 25 December, recording 16.07 (BRRI dhan89), 15.73 (BRRI dhan92), and 20.27 (BRRI dhan102). The lowest tiller counts were consistently observed on the 25 February transplanting date, with values of 11.33, 10.80, and 9.07, respectively.

A similar pattern was observed for panicles per hill (Fig. 3). Panicle production decreased steadily with delayed transplanting. The 25 December transplanting produced the maximum panicles—14.67 (BRRI dhan89), 13.93 (BRRI dhan92), and 18.87 (BRRI dhan102). The 25 February transplanting resulted in the lowest numbers: 9.93, 9.00, and 7.67, respectively.

The decline in tiller and panicle production at later dates is closely linked to increasing daytime temperatures during critical stages like panicle initiation. Early transplanting produced more tillers and panicles because the crop avoided high temperatures during the early reproductive stages. High temperatures above 33 °C are known to suppress tiller formation and inhibit panicle initiation (Sánchez et al., 2014). As shown in Fig. 1, temperatures exceeded 33 °C from mid-April onward, a threshold known to inhibit tillering and panicle formation.

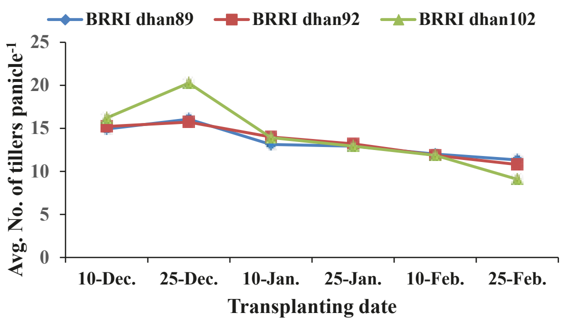

Fig. 2. Avg. No. of total tillers hill-1 of rice varieties as affected by transplanting dates during Boro 2023-24 season at Sagardi Farm, BRRI Regional Station, Barishal.

3.2. Filled grain and sterile spikelet percentage per panicle

Previous studies have highlighted the negative impact of late transplanting on filled grain production. Khan et al. (2022) reported up to a 14% reduction when planting was delayed to mid-February. Our results strongly support this trend.

The greatest number of filled grains per panicle was obtained from the 25 December transplanting for all varieties: 188.8 (BRRI dhan89), 173.0 (BRRI dhan92) and 146.27 (BRRI dhan102). By contrast, the 25 February transplanting produced critically low filled grain numbers: 13.67, 13.53, and 11.33, respectively (Fig. 4).

Spikelet sterility increased sharply with delayed transplanting (Fig. 5). Sterility exceeded 91% across all varieties on 25 February, while the earliest transplanting dates recorded the lowest sterility values. The sharp decrease in filled grains and the rise in spikelet sterility in late transplanting treatments were directly linked to heat stress. Temperatures near or above 35 °C during flowering can damage pollen mother cells, impair meiosis, and reduce fertilization, resulting in very high sterility (Endo et al., 2009; Wu et al., 2016). (Fig. 1 & Table 4). This explains the dramatic spikelet sterility observed in late transplanting treatments. Panicle density also dropped under late transplanting due to heat-induced spikelet degeneration (Fig. 3). Similar reductions have been reported under late-season heat (Sánchez et al., 2014).

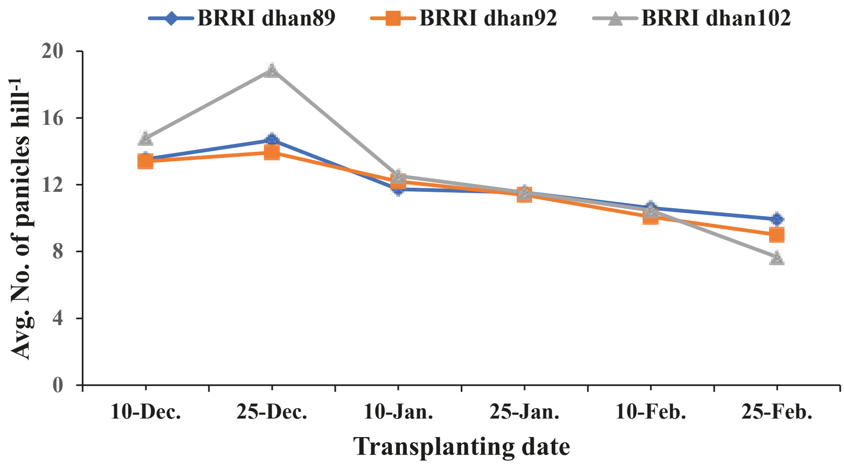

Fig. 3. Avg No. of total tillers hill^{-1} of rice varieties as affected by transplanting dates during Boro 2023-24 season at Sagardi Farm, BRRI Regional Station, Barishal.

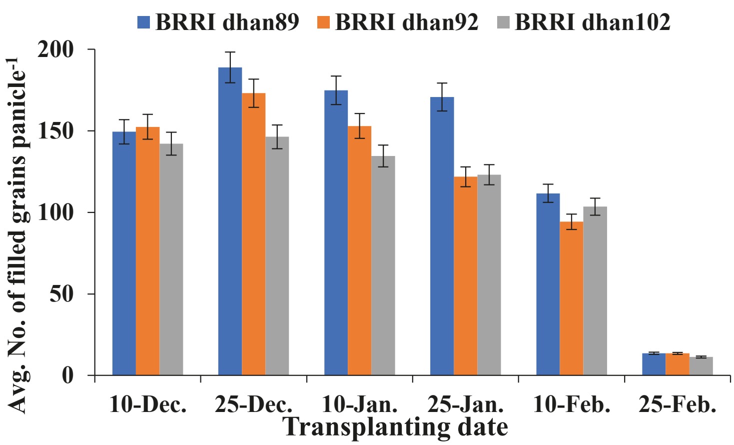

Fig. 4. Avg No. of filled grains panicle^{-1} of rice varieties as affected by transplanting dates during Boro 2023-24 season at Sagardi Farm, BRRI Regional Station, Barishal

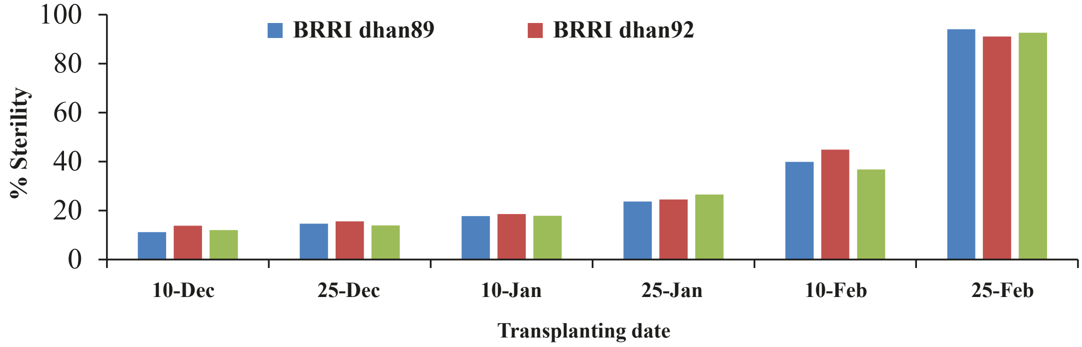

Fig. 5. Spikelet sterility of rice varieties as affected by transplanting dates during Boro 2023-24 season at Sagardi Farm, BRRI Regional Station, Barishal.

3.3. Panicles per square meter

Panicle density (panicles m^{-2}) varied significantly with transplanting dates (Table 3). Again, 25 December provided optimal conditions, producing the highest densities for BRRI dhan89 (492.71), BRRI dhan92 (353.13), and BRRI dhan102 (377.08).

The lowest densities occurred on 25 February, with notable declines to 275, 195.83, and 200 panicles m^{-2}, respectively. These reductions reflect suboptimal conditions for panicle initiation under late-season heat. High temperatures above 33 °C have been shown to impair panicle differentiation and promote spikelet degeneration (Sánchez et al., 2014), consistent with our findings. Thus, delayed transplanting restricts the formation of productive panicles, ultimately lowering yield potential.

3.4. Thousand-grain weight (TGW)

The TGW remained statistically unchanged across planting dates for BRRI dhan89 and BRRI dhan102. However, BRRI dhan92 showed significant variability, indicating greater sensitivity to heat stress during grain filling (Table 3).

For all varieties, the highest TGW was obtained on 25 December (22.82 g, 24.28 g, and 21.84 g for BRRI dhan89, BRRI dhan92, and BRRI dhan102, respectively). The lowest values appeared on 25 February, likely due to heat stress shortening the grain-filling duration and disrupting starch deposition (Arshad et al., 2017).

Table 3
Interaction effect of variety and transplanting date on grain yield and yield contributing characters during Boro 2023-24 season at Sagardi Farm, BRRI Regional Station, Barishal.

Variety	Transplanting date (DT)	Grain Yield (kg/ha)*	Panicle no. m^{-2}*	1000-Grain weight (g)*
BRRI dhan89	10-Dec.	5847.44b	304.69bc	20.02a
	25-Dec.	7233.49a	492.71a	22.82a
	10-Jan.	6562.09ab	322.4b	22.68a
	25-Jan.	4540.42c	302.08bc	22.07a
	10-Feb.	2913.3d	296.88bc	21.57a
	25-Feb.	215.41e	275c	19.33a
BRRI dhan92	10-Dec.	5819.77b	306.25b	23.46ab
	25-Dec.	7477.91a	353.13a	24.28a
	10-Jan.	6277.83b	316.67ab	22.06abc
	25-Jan.	4697.13c	295.83b	20.68bc
	10-Feb.	1929.69d	229.69c	18.83cd
	25-Feb.	405.85e	195.83c	16.45d
BRRI dhan102	10-Dec.	7310.7ab	371.8767a	20.27a
	25-Dec.	8097.82a	377.0833a	21.84a
	10-Jan.	6656.59b	310.42b	21.41a
	25-Jan.	4716.36c	277.6067bc	20.66a
	10-Feb.	3495.66d	248.9567c	20.6a
	25-Feb.	229.69e	200d	19.2a
LSD (0.05)		1008.0585	36.5771	3.5027
CV(DT)%		8.79	4.39	8.99
CV(Variety)%		8.68	5.1	4.92

* Means followed by the same lowercase letter in a column do not differ from each other at 5% level of significance.

3.5. Grain yield

Results clearly demonstrate that transplanting date profoundly influenced grain yield, confirming earlier studies (Al-Amin et al., 2019; Sarwar & Chanda, 2020). The highest yields were consistently recorded on 25 December: 7233.49 kg ha^{-1} (BRRI dhan89); 7477.91 kg ha^{-1} (BRRI dhan92); 8097.82 kg ha^{-1} (BRRI dhan102) (Table 4). Transplanting between 10 December and 10 January reliably produced yields exceeding 5000 kg ha^{-1}. Grain yield followed the combined pattern of tiller number, panicle density, filled grains, and sterility. The highest yields on 25 December matched previous reports that early transplanting ensures favorable temperature conditions for booting and flowering (Yang et al., 2020). Low yields in late planting were caused by heat stress, poor grain filling, and increased sterility.

Table 4
Interaction effect of variety and transplanting date on flowering, growth duration (GD), growing degree days (GDD) and heat use efficiency (HUE) during Boro season at Sagardi Farm, BRRI Regional Station, Barishal.

Variety	Transplanting date	50% Flowering date	100% Flowering date	Growth duration (days)*	GDD at maturity stage(°C)*	Heat use efficiency*
BRRI dhan89	10-Dec.	18-Mar.	26-Mar.	175.0a	2363.4b	2.47b
	25-Dec.	29-Mar.	02-Apr.	160.33c	2112.97d	3.42a
	10-Jan.	07-Apr.	12-Apr.	157.67d	2170.32c	3.03a
	25-Jan.	09-Apr.	14-Apr.	147.0e	2067.3e	2.2b
	10-Feb.	01-May	06-May	145.0f	2189.6c	1.33c
	25-Feb.	21-May	27-May	163.0b	2747.55a	0.08d
BRRI dhan92	10-Dec.	22-Mar.	27-Mar.	175.0a	2363.4b	2.46bc
	25-Dec.	28-Mar.	02-Apr.	161.0c	2128.43d	3.51a
	10-Jan.	07-Apr.	12-Apr.	156.33d	2146.12d	2.93b
	25-Jan.	11-Apr.	15-Apr.	147.67e	2078.9e	2.26c
	10-Feb.	02-May	08-May	147.67e	2234.07c	0.86d
	25-Feb.	21-May	27-May	163.0b	2747.55a	0.15e
BRRI dhan102	10-Dec.	24-Mar.	31-Mar.	178.0a	2432.2a	3.01b
	25-Dec.	29-Mar.	01-Apr.	159.67b	2097.33c	3.86a
	10-Jan.	07-Apr.	14-Apr.	156.67c	2151.35b	3.09b
	25-Jan.	09-Apr.	14-Apr.	146.33d	2055.7d	2.29c
	10-Feb.	24-Apr.	30-Apr.	141.33e	2111.77c	1.65d
	25-Feb.	05-May	11-May	148.0d	2440.4a	0.09e
LSD (0.05)		-	-	1.7255	33.6781	0.4829
CV(DT)%		-	-	0.5267	0.6742	9.06
CV(Variety)%		-	-	0.3921	0.5637	9.14

* Means followed by the same lowercase letter in a column do not differ from each other at 5% level of significance

In stark contrast, the 25 February transplanting resulted in severe yield collapse (215–406 kg/ha), driven by extreme spikelet sterility, low panicle density, and impaired grain filling. High temperatures during booting, flowering, and grain filling are widely recognized as major constraints for yield and grain quality (Yang et al., 2020). Heat stress also alters starch biosynthesis and amylose content (Ahmed et al., 2015), while high night-time temperatures further aggravate yield losses (Xu et al., 2021).

3.6. Growing degree days (GDD) and heat use efficiency (HUE)

Cumulative GDD values at maturity were highest for the 25 February transplanting date for BRRI dhan89 and BRRI dhan92 (2747.55 °C) and BRRI dhan102 (2440.4 °C). Early transplanting dates accumulated fewer heat units (Table 4).

However, higher GDD did not translate into higher yields. Correlation analysis showed a weak negative relationship between GDD and grain yield, indicating that excessive heat accumulation was detrimental to productivity.

Heat Use Efficiency followed a clearer pattern: highest HUE occurred on 25 December (3.42–3.86); lowest HUE occurred on 25 February (0.08–0.15). These results agree with Nayak et al. (2017), who reported higher HUE under early transplanting. Our findings confirm that rice plants utilize heat energy most efficiently when transplanted within the optimal window of late December to early January.

One primary mechanism driving this yield advantage is the alignment of sensitive reproductive stages with favorable thermal environments. Rice development is closely associated with accumulated thermal units, such as GDD and HUE, which integrate temperature and solar radiation influences into crop growth processes. Optimal sowing dates ensure that flowering and grain-filling phases occur under milder temperatures and adequate light conditions, promoting better spikelet fertility, efficient assimilate partitioning, and enhanced grain filling (Halder et al., 2025). Observational studies have demonstrated that variations in sowing date substantially affect accumulated GDD for key phenological phases, with delayed sowing modifying the duration and thermal accumulation patterns, ultimately influencing yield potential (Halder et al., 2025).

4. Conclusion

This study clearly shows that the optimal transplanting window, from 10 December to 10 January, experiences favorable temperature conditions that support vigorous growth and high productivity in the Barishal region. Transplanting after this window exposed the crop to elevated temperatures during critical reproductive stages, leading to increased spikelet sterility and substantial yield reductions. These results underscore how sensitive rice is to temperature fluctuations and emphasize the importance of synchronizing transplanting time with key developmental phases to mitigate the impacts of heat stress. However, to enhance the broader applicability and robustness of these results, similar trials should be conducted across diverse farmers' fields and under varying management practices. Because environmental conditions can differ significantly across regions, region-specific validation is essential. Therefore, it is recommended that comparable experiments be carried out in other rice-growing areas of Bangladesh. Expanding this research will help generate more comprehensive and regionally relevant recommendations, ultimately supporting farmers nationwide in optimizing transplanting time, reducing heat-related yield losses, and ensuring more stable Boro rice production.

References

Ahmed, N., Tetlow, I.J., Nawaz, S., Iqbal, A., Mubin, M., Rehman, M.S.N.U., Butt, A., Lightfoot, D.A. and Maekawa, M. 2015. Effect of high temperature on grain filling period, yield, amylose content and activity of starch biosynthesis enzymes in endosperm of basmati rice. J. Sci. Food Agric., 95(11): 2237–2243.

Al-Amin, M., Nasrin, S., Mabud, A.K.M.G. and Sani, M.N.H. 2019. Effect of planting date on the performance of high yield potential varieties of rice in Bangladesh. Asian J. Agric. Rural Dev., 9(4): 1–11.

Arshad, M.S., Farooq, M., Asch, F., Krishna, J.S.V., Prasad, P.V.V. and Siddique, K.H.M. 2017. Thermal stress impacts reproductive development and grain yield in rice. Plant Physiol. Biochem., 115: 57–72.

BRRI. 2025. Modern Rice Cultivation. 25th ed. Bangladesh Rice Research Institute, Gazipur, Bangladesh. pp. 14–27.

Deshmukh, S.P. and Patel, J.G. 2013. Influence of non-monetary and low-cost input in sustainable summer pearl millet (*Pennisetum glaucum* L.) production. Int. J. Agric. Food Sci. Technol., 4(6): 579–588.

Endo, M., Tsuchiya, T., Hamada, K., Kawamura, S., Yano, K., Ohshima, M., Higashitani, A., Watanabe, M. and Kawagishi-Kobayashi, M. 2009. High temperatures cause male sterility in rice plants with transcriptional alterations during pollen development. Plant Cell Physiol., 50(11): 1911–1922.

Farrell, T.C., Fox, K., Williams, R.L., Fukai, S. and Lewin, L.G. 2003. Avoiding low temperature damage in Australia's rice industry with photoperiod sensitive cultivars. In: Proceedings of the 11th Australian Agronomy Conference. Deakin University, Geelong, Victoria, Australia.

Gomez, K.A. and Gomez, A.A. 1984. Statistical Procedures for Agricultural Research. 2nd ed. John Wiley & Sons, New York. pp. 97–111.

Gurleen, K., Sreethu, S., Vikas, S. and Vandna, C. 2025. Heat use efficiency and yield optimization in wheat as influenced by irrigation scheduling. Journal of Agrometeorology 27 (4): 442-446.

Halder, T., Biswas, A., Barman, H.N., Akter, S., Shupta, S.A. and Pervin, M.S. 2025. Thermal requirement for the phenological development and yield of rice as influenced by seeding date. Bangladesh Rice J., 27(2): 39–50.

Harbinson, J., Parry, M.A.J., Davies, J., Rolland, N., Loreto, F., Wilhelm, R. and Metzlaff, K. 2021. Designing the crops for the future: The Crop Booster Program. Biology, 10(7): 690.

Islam, S.M.F. and Karim, Z. 2019. World's demand for food and water: The consequences of climate change. In: Desalination – Challenges and Opportunities.

Jamal, M.R., Kristiansen, P., Kabir, M.J. and Lobry, D.B. 2023. Challenges and adaptations for resilient rice production under changing environments in Bangladesh. Land, 12(6): 1217.

Khalifa, A.A.B. 2009. Physiological evaluation of some hybrid rice varieties under different sowing dates. Aust. J. Crop Sci., 3(3): 178–183.

Khan, M.N.A., Hossain, M.B., Biswas, P.K., Amin, A.R. and Rahman, A. 2022. Influence of transplanting date on performance of Boro rice varieties in Lalmai-hill area. SAARC J. Agric., 20(1): 143–155.

Khan, M.A.I., Ueno, K., Horimoto, S., Komai, F., Tanaka, K. and Ono, Y. 2009. Physicochemical, including spectroscopic, and biological analyses during composting of green tea waste and rice bran. Biology and Fertility of Soils 45: 305-313.

Liu, L.W., Lu, C.T., Wang, Y.M., Lin, K.H., Ma, X., Lin, W.S. 2022. Rice (*Oryza sativa* L.) growth modeling based on growth degree day (GDD) and artificial intelligence algorithms. Agriculture, 12, 59. https://doi.org/10.3390/agriculture12010059

Mukesh, I., Singh, R.K., Pannu, D., Prasad, D. and Ram, A. 2013. Effects of different transplanting dates on yield and quality of basmati rice (*Oryza sativa* L.) varieties. Indian J. Agron., 58(2): 256–258.

Nayak, B.R., Panigrahy, N., Mohapatra, S., Mohanty, A.K., Sahoo, B., Jagdev, P.N. and Patel, S. 2017. Heat utilization and productivity of summer transplanted rice (*Oryza sativa* L.) in relation to irrigation schedules and date of transplanting. J. Agrometeorol., 19(3): 242–245.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X. and Cassman, K.G. 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. U.S.A., 101(27): 9971–9975.

Rani, B.A. and Maragatham, N. 2013. Effect of elevated temperature on rice phenology and yield. Indian J. Sci. Technol., 6(8): 5095–5097.

Reddy, S.N. and Narayana, P. 1984. Pattern of dry matter accumulation and N uptake by rice as influenced by age of seedling and date of planting. Andhra Agric. J., 32: 155–156.

Sánchez, B., Rasmussen, A. and Porter, J.R. 2014. Temperatures and the growth and development of maize and rice: A review. Glob. Change Biol., 20(2): 408–417.

Sarwar, A.K.M.G. and Chanda, S.C. 2020. Growth and yield descriptors of rice influenced by transplanting date. J. Agric. Food Environ., 1(4): 48–52.

Shrestha, S., Mahat, J., Shrestha, J. and Paudel, K. 2022. Influence of high-temperature stress on rice growth and development: A review. Heliyon, 8(12): e12651.

STAR. 2014. STAR Version 2.0.1. Biometrics and Breeding Informatics, Plant Breeding Division, International Rice Research Institute, Los Baños, Philippines.

United States Department of Agriculture. 2020. World Agricultural Production: Rice Production by Country.

Vange, T. and Obi, I.U. 2006. Effect of planting date on some agronomic traits and grain yield of upland rice varieties at Makurdi, Benue State. Niger. J. Sustain. Dev. Agric. Environ., 2(1): 1–9.

Wu, C., Cui, K., Wang, W., Li, Q., Fahad, S., Hu, Q., Huang, J., Nie, L. and Peng, S. 2016. Heat-induced phytohormone changes are associated with disrupted early reproductive development and reduced yield in rice. Sci. Rep., 6: 34978.

Xu, J., Misra, G., Sreenivasulu, N. and Henry, A. 2021. What happens at night? Physiological mechanisms related to maintaining grain yield under high night temperature in rice. Plant Cell Environ., 44(7): 2245–2261.

Yang, J., Zhang, Y.Z., He, H.H., Li, Y.C., Chen, X.R., Bian, J.M., Jin, G.H., Li, X.X. and Huang, S.E. 2020. Current status and research advances of high-temperature hazards in rice. J. Appl. Ecol., 31(8): 2817–2830.

Yang, Z., Zhang, Z., Zhang, T., Fahad, S., Cui, K., Nie, L. and Peng, S. 2017. The effect of season-long temperature increases on rice cultivars grown in the central and southern regions of China. Front. Plant Sci., 8: 1908.

Yan, W., Hunt, L.A., Sheng, Q. and Szlavnics, Z. 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Sci., 40: 597–605.

Yoshida, S. and Parao, F.T. 1976. Climatic influence on yield and yield components of lowland rice in the tropics. In: Climate and Rice. pp. 471–494.

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Present Scenario and Future Outlook of Precipitation in the Boro Season of Bangladesh

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A B S T R A C T

Bangladesh's economy still relies heavily on agriculture, which is intrinsically tied to climate. Climate change threatens the country's food security. Accurately forecasting future climatic conditions is essential for strategic agricultural planning and adaptation. The Boro season (January through April) constitutes one of Bangladesh's primary cropping periods, and many crops, especially rice, depend on rainfall. The objective of this study is to generate precipitation maps for Bangladesh over three periods: 1970–2000 (past), 2000–2018 (present), and 2040–2060 (future, around 2050), focusing on January through April. We used projected outputs from CMIP5 and CMIP6 global climate models and applied GIS techniques—raster statistics, raster extraction, and zonal statistics—to compile, analyze, and visualize the data. The results indicate that by 2050, rainfall is expected to increase by approximately 5–10 mm during January to March, while April precipitation will decline by about 3–6 mm compared to the 2010–2018 baseline. Such an increase is relatively small and generally within crop tolerance, meaning it is unlikely to negatively affect yield under normal drainage conditions. However, the projected increases in precipitation are relatively modest, they may pose localized challenges in poorly drained areas or during critical crop growth stages. Consistent with historical patterns, eastern Bangladesh is projected to receive the highest precipitation by 2050, while the northwestern region remains comparatively drier. These spatially explicit findings provide a scientific basis for region-specific.

1. Introduction

Bangladesh's economy relies heavily on agriculture (BER, 2020; Rahman et al., 2020). At present, the agricultural sector contributes 13.02 percent to the country's GDP. The performance of agriculture in any country is shaped by its meteorological conditions (Aziz et al., 2021). Weather and climate consistently pose risks to economic stability (Parker et al., 2019; Rahman et al., 2015; Farhan et al., 2022). One of the most critical factors shaping the future of global food security is the effect of climate change on agriculture (Yu et al., 2010). Rice is particularly important in this regard, as it is Bangladesh's staple food and covers more than 90 percent of the total net cropped area (Islam et al., 2019). While breeding advanced rice

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germplasm build crop resilience (Hasan et al., 2025) tracking climate ships remain essential to ensure these new varieties actually thrive under future conditions (Hussain et al., 2015). Key climate variables that affect rice production include temperature, rainfall, atmospheric CO2 concentration, and solar radiation (Amin et al., 2015; Ali et al., 2017). Any shift in rainfall patterns increases the chances of short-term crop failure as well as long-term yield loss (IFPRI, 2010).

Since the pre-industrial era, global greenhouse gas emissions have risen dramatically. The increasing volume of these gases has been the main driver of global warming over the last century (Yang et al., 2012). Rising global temperatures directly affect rainfall and temperature patterns, resulting in higher evaporation rates and greater surface drying, which intensify the severity and duration of droughts (Trenberth, 2011). Like many other countries, Bangladesh is experiencing the destructive effects of climate change (Das et al., 2024). Current greenhouse gas emissions are more than 27 and 50 percent higher from agriculture and waste management sector respectively than they were in 1990 (Chowdhury et al., 2020). Greenhouse gas emissions affect rainfall by intensifying the hydrological cycle, altering atmospheric moisture transport and circulation, which in turn changes precipitation intensity, seasonality, and spatial distribution. The climate system is now undergoing long-term shifts due to global warming, and these could have irreversible consequences if left unaddressed. Using machine learning and deep learning algorithms to predict temperature fluctuations bridges the gap between climate datasets and accurate projections of global climate shift. (Rahman et al., 2025; Rahman et al., 2026)

To respond to this challenge, the United Nations introduced the Sustainable Development Goals, with Goal 13 specifically focused on climate action (Rahman, 2021). Achieving this requires aligning climate strategies with disaster risk reduction, sustainable management of natural resources, and social protection within national development policies. It is still possible to limit the global average temperature rise to two degrees Celsius above pre-industrial levels, and ideally to 1.5°C, but this depends on strong political commitment, larger investments, and the use of available technologies (Hoegh-Guldberg et al., 2019). Such outcomes, however, demand urgent and ambitious collective measures. Addressing these concerns also connects directly with the climate-related challenges of the Fourth Industrial Revolution (Cole, 2021).

Bangladesh's food security is, above all, dependent on rice security (Rahman et al., 2021; Shozib et al., 2020; Kulsum et al., 2015). A large amount of water is required for proper growth of rice, making rainfall a vital factor in providing irrigation for rice production and reducing pressure on groundwater. The cropping pattern of Bangladesh is divided into three distinct seasons: Boro rice season (December to May), Aus rice season (March to August) and Aman rice season (June to November) (Sarker et al., 2012; Islam et al., 2022). Among these, the Boro season is the most diversified, and crops grown during this period are commonly referred to as winter crops in Bangladesh. The sowing of Boro crops such as Boro rice, wheat, cauliflower, cabbage, potato, carrot, radish, broccoli, and tomato usually begins in November–December and transplanted during December–January, although timing differs depending on the region. In the northern areas, winter arrives earlier, so crop sowing starts sooner compared to other regions. Winter crops generally perform well under low to moderate precipitation, particularly during establishment. In Bangladesh, the winter season is characterized by minimal rainfall, which supports controlled water management and favorable growing conditions for winter crop cultivation.

However, climate change has made noticeable shifts in spatio-temporal climatic variables. January is the coldest month in Bangladesh, and severe cold during January and February is a major reason for spikelet sterility in rice and wheat as well as reduced yields of winter vegetables (Prodhan et al., 2018; Rashid and Yasmeen, 2018; Sharmin et al., 2018).

In addition, cold weather increases the risk of seedling blight in rice and negatively impacts seed germination (Ansari & Ahmed, 2017). From March to May, the months just before the monsoon season, excessively high temperatures and delayed rainfall often dry out pollen and stigma, leading to empty spikelets in rice and wheat and reducing fruit set in crops like tomato and brinjal (Firon et al., 2006; Rahman et al., 2017; Tomás et al., 2020).

To address these challenges, policymakers require updated knowledge of future climate impacts to harmonize human society with natural systems (Miao et al., 2014). Climate models play a crucial role in understanding how the climate responds to different influences, producing seasonal to decadal predictions, and generating long-term projections for the coming centuries (Flato et al., 2014). The Coupled Model Intercomparison Project (CMIP) is a global collaboration in climatology aimed at enhancing understanding of climate change. Its fifth phase (CMIP5) has produced an advanced multi-model dataset to improve knowledge of climate variability and change. More than 20 modeling teams have contributed over 50 models to CMIP5 simulations (Taylor et al., 2012).

Climate model–based precipitation projections indicate that climate change is likely to modify rainfall intensity, seasonality, and spatial distribution across South Asia, including Bangladesh. CMIP-based studies consistently suggest an intensification of the hydrological cycle, with increases in monsoon rainfall variability and a higher likelihood of extreme precipitation events, alongside changes in dry-season rainfall (Odunmorayo et al., 2025). However, large uncertainties remain in simulating precipitation due to complex interactions among atmospheric circulation, land–surface processes, and regional topography, particularly in deltaic and monsoon-dominated regions. As a result, downscaled and region-specific precipitation assessments are essential for translating global climate projections into actionable information for national and sub-national planning.

Only a limited number of studies have projected precipitation scenarios for Bangladesh. Rahman et al. (2019) developed a climate simulation model for Bangladesh covering 1979–2006. Dastagir, M. R. (2015) created a climate change model with fine spatial resolution of 20 km to 50 km but faced issues of low confidence. Bosu (2020) produced a projected precipitation map for 2050–74, and Mondal, M. S. (2020) created an average annual rainfall map for 2041–60, although both focused only on annual totals and did not provide monthly precipitation forecasts.

Given ongoing climate change, forecasting future conditions is essential for coping with its impacts and ensuring food security in Bangladesh. Both the Government of Bangladesh and the United Nations' Sustainable Development Goals (SDGs) emphasize the need to build climate-resilient agricultural systems to safeguard food security (Rahman et al., 2021). Because Bangladesh's agriculture is highly rainfall-dependent, uncertainties in future precipitation pose a major challenge for crop planning, irrigation management, and risk reduction. In particular, the Boro season (January–April) is critically sensitive to rainfall variability, as insufficient or poorly timed precipitation can increase irrigation demand, production costs, and vulnerability to drought or water stress.

Despite this importance, existing climate studies in Bangladesh have largely focused on annual or monsoon-season rainfall, providing limited guidance for dry-season, crop-specific decision-making. The lack of reliable, region-specific monthly precipitation projections for the Boro season restricts the ability of policymakers and farmers to anticipate future water availability and design effective adaptation strategies. This gap is especially problematic given the spatial heterogeneity of rainfall across Bangladesh, where regional differences strongly influence agricultural outcomes.

Therefore, this research aims to project future rainfall scenarios for the year 2050 during the Boro season (January–April), both at the national and divisional levels, using CMIP5 climate model outputs integrated with GIS techniques. By comparing projected precipitation with observed rainfall patterns, this study provides a robust assessment of potential future changes. The findings offer region-specific insights that can support climate-resilient crop planning, irrigation scheduling, and policy formulation. Moreover, the GIS-based precipitation maps developed in this study can assist policymakers and researchers in optimizing resource allocation, strengthening early warning systems, and enhancing long-term food security planning under changing climatic conditions in Bangladesh.

2. Materials and methods

2.1. Study Area

Bangladesh is located in South-East Asia, extending from 20°34'N to 26°38'N latitude and 88°01'E to 92°41'E longitude. The country consists mainly of low-lying plains covering 147,570 square kilometers, bordered by the Meghalaya Plateau and West Bengal to the north, the Bay of Bengal to the south, the Assam hills to the east, and the West Bengal and Gangetic Plains to the west (Chowdhury et al., 2021). Climatic parameters in Bangladesh are strongly influenced by the Himalayan Mountains in the north and the Bay of Bengal in the south. Rainfall patterns in Bangladesh are more distinct and cyclical compared to temperature. Spatial and temporal variations in rainfall are significant, with maximum rainfall (about 400 cm) occurring in the northeast and minimum rainfall (about 150 cm) in the west-central region. The southeastern districts of Cox's Bazar and Bandarban, along with the northern part of Sylhet, receive the highest annual rainfall in the country (Wheeler, 1999).

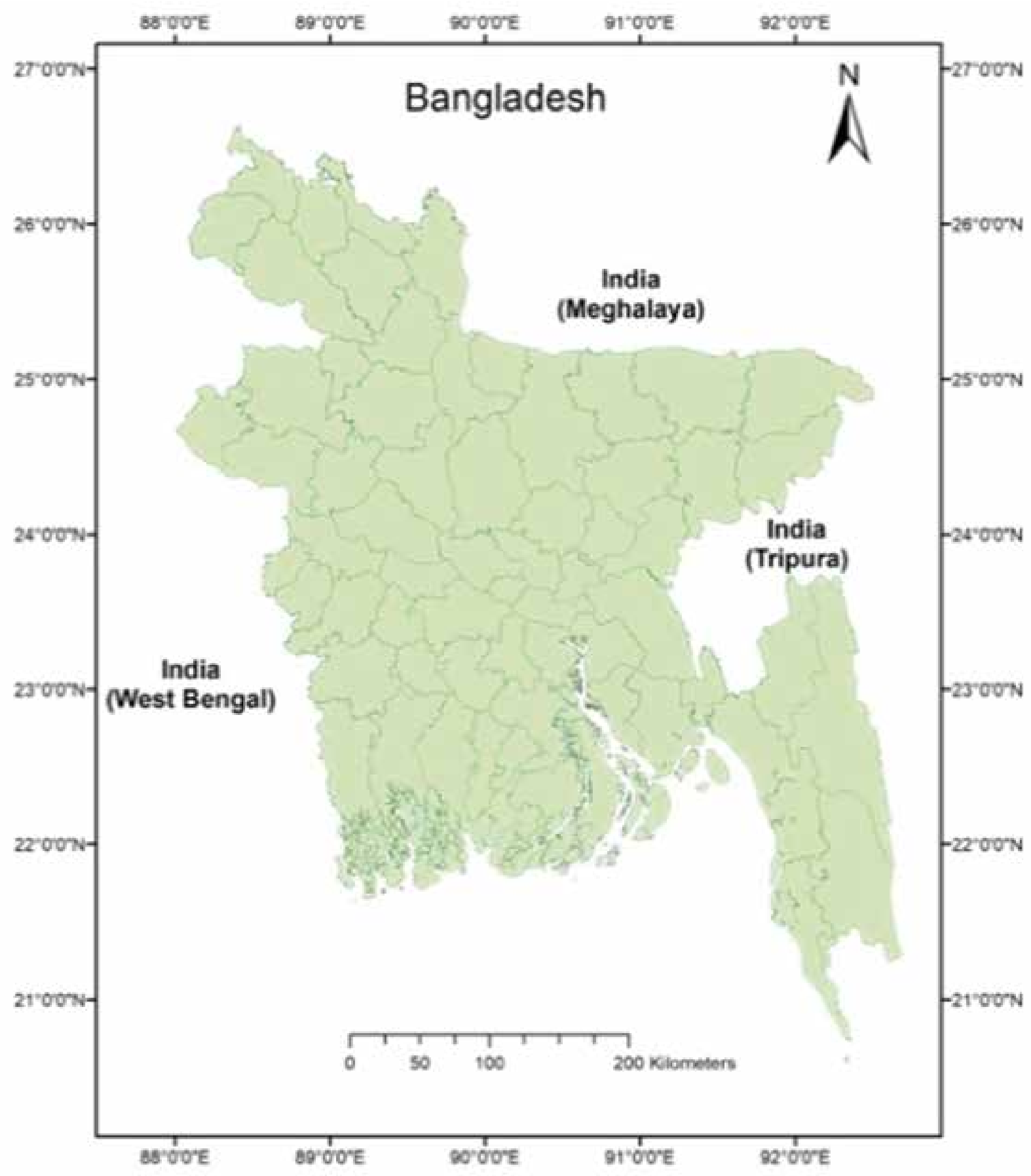

Fig. 1. Study Area Map.

2.2. Data source

In this study, the most widely used and freely accessible climate raster datasets of precipitation, WORLDCLIM 1.4 and its updated version WORLDCLIM 2.1 (Fick and Hijmans, 2017), were utilized. To analyze long-term precipitation patterns, the timeline was separated into three categories: past (1970 to 2000), present (2010 to 2018), and future (2040 to 2060). A summary of the dataset is presented in Table 1.

Table 1
List of datasets used in this study.

Climate Period	Climate Dataset	CMIP Phase	Author	Data Format	Obtained Spatial Resolution	Obtained Source
Past (1970-2000)	WORLDCLIM1.4	CMIP6	Hijmans et al., 2005	Raster	2.5 arc minutes resolution	https://www.worldclim.org/data/monthlywth.html
Present (2010-2018)	WORLDCLIM2.1	CMIP6	Fick and Hijmans 2017	Raster	2.5 arc minutes resolution	https://www.worldclim.org/data/worldclim21.html
Future (2040-2060)	WORLDCLIM1.4	CMIP5	Hijmans et al., 2005	Raster	2.5 arc minutes resolution	https://www.worldclim.org/data/monthlywth.html

Raster data consist of pixels, also referred to as grid cells. These cells are generally square and evenly spaced, although this is not mandatory. Since each pixel holds its own data value or class, raster datasets usually appear pixelated (GISGeography, 2021).

Global Climate Models (GCMs)

A total of 19 CMIP5 Global Climate Models (GCMs) were accessed from WORLDCLIM 1.4 (Fick and Hijmans, 2017) to project future precipitation (Table 2).

Table 2
List of CMIP5 global climate models used for forecasting projected precipitation in this study.

Model	Resolution	Modeling group	Obtained Source	Obtained Resolution
ACCESS1-0 (#)	1.9° × 1.3°	CSIRO-BOM, Australia	WORLDCLIM 1.4 (https://www.worldclim.org/data/monthlywth.html)	2.5 arc minutes resolution
BCC-CSM1-1	2.8° × 2.8°	Beijing Climate Center, China Meteorological Administration, China		
CCSM4	1.3° × 0.9°	National Center for Atmospheric Research (NCAR), USA		
CESM1-CAM5-1-FV2	1.3° × 0.9°	National Science Foundation, Department of Energy, NCAR, USA		
CNRM-CM5 (#)	1.4° × 1.4°	Centre National de Recherches Meteorologiques, France		
GFDL-CM3	2° × 2°	NOAA/Geophysical Fluid Dynamic Laboratory, United States		
GFDL-ESM2G	2° × 2°	NOAA/Geophysical Fluid Dynamic Laboratory, United States		
GISS-E2-R	2° × 2°	NASA Goddard Institute of Space Studies, United States		
HadGEM2-AO	1.9° ×.3°	National Institute of Meteorological Research/Korea Meteorological Administration, Korea		
HadGEM2-CC	1.9° × 1.3°	Met Office Hadley Centre (additional HadGEM2-ES realisations contributed by Instituto Nacional de Pesquisas Espaciais), UK		
HadGEM2-ES	1.9° × 1.3°	Met Office Hadley Centre (additional HadGEM2-ES realisations contributed by Instituto Nacional de Pesquisas Espaciais), UK		
INMCM4	2° × 1.5°	Institute for Numerical Mathematics, Russia		
IPSL-CM5A-LR	3.8° × 1.9°	Institut Pierre-Simon Laplace, France		
MIROC-ESM-CHEM (#)	2.8° × 2.8°	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan		
MIROC-ESM (#)	2.8° × 2.8°	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan		
MIROC5 (#)	1.4° × 1.4°	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan		
MPI-ESM-LR	1.8° × 1.8°	Max Planck Institute for Meteorology (MPI-M), Germany		
MRI-CGCM3	1° × 1°	Meteorological Research Institute, Japan		
NorESM1-M	2° × 2°	Norwegian Climate Centre, Norway		

The main focus of this research was projecting future precipitation under four Representative Concentration Pathways (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). These RCPs represent low (2.6), medium (4.5), high (6.0), and very high (8.5) scenarios, with radiative forcing values of 2.6, 4.5, 6.0, and 8.5 W/m^2, respectively, by the year 2100 (Miao et al., 2014).

An RCP is defined by the Intergovernmental Panel on Climate Change (IPCC) as a greenhouse gas concentration pathway rather than an emissions trajectory. The IPCC Fifth Assessment Report (AR5, 2014) highlights four pathways that can be applied for climate research and modeling. These represent different but plausible climatic futures, depending on the amount of greenhouse gases (GHG) released in the future (Moss et al., 2008).

RCP 2.6

RCP 2.6 is the lowest-emission scenario among the four Representative Concentration Pathways (RCPs) defined by the IPCC for climate modeling. The Pathway explains that carbon dioxide (CO2) emissions must peak around 2020 and reach net zero by 2100. It also aims to cut methane (CH4) emissions by half and sulfur dioxide (SO2) emissions by about 10 percent compared to their 2020 and 1980–1990 levels, respectively. By 2100, RCP 2.6 seeks to limit global temperature rise to below 2˚C (IPCC, 2014: Climate Change 2014: Synthesis Report).

RCP 4.5

RCP 4.5 is regarded as a mid-level scenario by the IPCC. In this pathway, emissions peak around 2040 and then begin to decline. Its objective is to keep the global temperature rise within 2–3˚C by 2100, with sea level rise limited to less than 35 percent higher than that of RCP 2.6 (Team et al., 2015).

RCP 6.0

This scenario assumes a stabilized condition, where radiative forcing levels off after 2100. It involves the use of different technologies and strategies to mitigate greenhouse gas emissions (Fujino et al., 2006).

RCP 8.5

RCP 8.5 represents a pathway where greenhouse gas emissions continue to rise throughout the 21st century. It was originally based on an overestimation of coal use and is often treated as the worst-case climate change projection. However, researchers argue that the RCP 8.5 pathway is becoming increasingly realistic with time (Hausfather & Peters, 2020).

2.3. Analytycal methods

The methodology of this research is organized into two main steps, employing GIS techniques such as raster statistics, raster extraction, and zonal statistics.

Step-1: Compilation and Processing of Climate Data

GCM data were collected from open-access sources, and raster statistics processing was carried out using ArcGIS 10.8. The cell statistics tool was applied to compute the mean of multiple monthly raster files from different years, producing one raster file per month. This tool works by analyzing cell values across several rasters pixel by pixel and assigning a calculated value for each location on the output raster. The mean function was selected to derive the average precipitation values.

Step-2: Preparation of Precipitation Projection Map

To extract location-specific information, the raster extraction technique was used. The extract by mask process was applied, which isolates raster cells corresponding to the designated study area from the averaged raster data. Afterward, the zonal statistics tool was employed to generate division-wise precipitation estimates based on administrative boundaries. The mean statistics function was chosen to calculate division-level precipitation values. Using ArcGIS 10.8, division-wise maps as well as country-level precipitation maps were prepared for the past (1970 to 2000) and the future (2040 to 2060, or 2050).

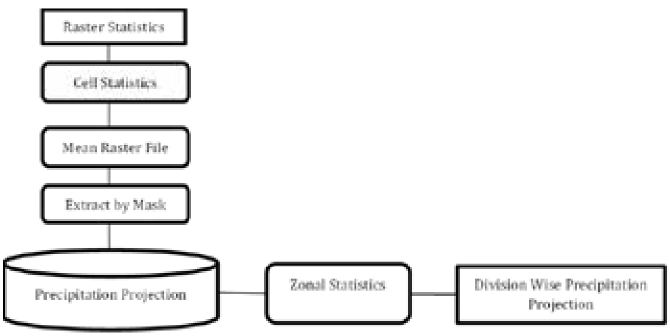

Fig. 2. Methodological Framework.

3. Results

3.1. Precipitation of January

Table 3 indicates the average precipitation in January between 1970 and 2000 in Bangladesh. The results indicate higher precipitation in the northeast and lower northwest regions, moderate precipitation in the central part, and the lowest levels in the southeast. Division-wise analysis reveals that Rajshahi recorded the highest average precipitation (12.29 mm), followed by Sylhet (11.78 mm), while Chattogram had the lowest (7.23 mm). It also shows the average January precipitation during 2010–2018, when the highest rainfall was again in the northeast, followed by the lower northwest, with moderate levels in central Bangladesh and the lowest in the southeast. Division-wise analysis for 2010–2018 shows that Sylhet had the highest average precipitation (8.76 mm), followed by Rajshahi (8.01 mm). Notably, during the earlier period (1970 to 2000), Rajshahi was the highest, and the lowest shifted from Chattogram to Dhaka division (5.18 mm).

The projected average precipitation for January 2050 under the RCP 2.6 scenario. The pattern is similar to earlier observations: the northeast and lower northwest will experience the highest rainfall, the central part moderate rainfall, and the southeast the lowest. Division-level analysis suggests that Sylhet and Rajshahi will both reach the highest average precipitation (12.27 mm), while Chattogram will have the lowest (6.82 mm).

The projected January precipitation for 2050 using the RCP 4.5 scenario. The results are broadly consistent with RCP 2.6, with Sylhet (11.56 mm) and Rajshahi (11.08 mm) recording the highest rainfall and Chattogram the lowest (6.23 mm).

It also illustrates the projected January average precipitation in Bangladesh under the RCP 6.0 model. The rainfall distribution pattern is nearly identical to what was found in the RCP 2.6 and RCP 4.5 models. The results show that in 2050, Sylhet will receive the highest precipitation (14.03 mm), followed by Rajshahi (13.79 mm), while Chattogram will experience the lowest (7.98 mm).

The table also contain the projected January average precipitation for 2050 under the RCP 8.5 model. The overall precipitation distribution is very similar to that of the RCP 2.6, 4.5, and 6.0 models, with the only difference being a decline in rainfall in the central southern part of the country. Under this scenario, Sylhet is expected to have the highest precipitation (13.53 mm), followed by Rajshahi (12.67 mm), while Chattogram will again record the lowest (7.38 mm) in 2050.

Table 3
Comparison of average total precipitation in January across 1970–2000, 2010–2018, and the 2050 forecast (Based on RCP models 2.6, 4.5, 6.0, and 8.5).

Division	Average Precipitation (mm) 1970 to 2000	Average Precipitation (mm) 2010 to 2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050(RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Rangpur	9.8	6.8	9.6	8.13	10.26	9.5	9.3725	2.5725
Rajshahi	12.29	8.01	12.27	11.08	13.79	12.67	12.4525	4.4425
Khulna	11.65	6.43	10.71	10.33	12.96	11.49	11.3725	4.9425
Mymensingh	9.15	6.83	10.81	9.89	12.26	11.28	11.06	4.23
Sylhet	11.78	8.76	12.27	11.56	14.3	13.53	12.915	4.155
Dhaka	7.54	5.18	8.71	8.34	10.26	9.25	9.14	3.96
Barishal	8.55	5.19	8.47	8.01	10.29	9.18	8.9875	3.7975
Chattogram	7.23	5.42	6.82	6.23	7.98	7.38	7.1025	1.6825

3.2. Precipitation of February

Table 4 presents the average precipitation scenario for February between 1970 and 2000 in Bangladesh. The northeastern region received the highest rainfall, followed by the southwestern part. Both the northern and southern central regions experienced moderate rainfall, while the southeastern region had the lowest precipitation. Division-wise analysis indicates that in February between 1970 and 2000, Barishal received the highest precipitation (28.07 mm), followed by Sylhet (27.44 mm). Rangpur had the lowest with an average of 11.85 mm.

It also shows the February precipitation scenario for 2010–2018. During this period, the highest rainfall was observed in the northeastern part, followed by the southwestern side, with central Bangladesh experiencing moderate rainfall and the southeastern side having the lowest. Division-wise data reveal that Sylhet recorded the highest precipitation (18.01 mm), followed by Khulna (15.74 mm), while the lowest shifted from Rangpur (in 1970–2000) to Chattogram

(10.02 mm).

The projected average precipitation for February in 2050 under the RCP 2.6 scenario. The northeastern region is expected to receive the highest rainfall, while central areas will see moderate amounts. The lowest precipitation is forecasted for the northwestern and parts of the southeastern regions. At the division level, Sylhet is projected to receive the highest rainfall (22.35 mm), while Rangpur will experience the lowest (9.51 mm).

It also noticeable from the table that the rainfall pattern is almost identical to that of RCP 2.6. Here, Sylhet is expected to record the highest precipitation (29.22 mm), followed by Barishal (25.86 mm), while Chattogram will receive the lowest (11.07 mm) in 2050. Precipitation projection for February under the RCP 6.0 scenario. The overall rainfall pattern is again similar to the RCP 2.6 and 4.5 models. Under this scenario, Sylhet is forecasted to receive the highest rainfall (26.92 mm), followed by Barishal (23.8 mm), while Rangpur will have the lowest (10.33 mm) in 2050, and the February precipitation forecast for 2050 under the RCP 8.5 scenario shows that the distribution is nearly the same as under the RCP 2.6, 4.5, and 6.0 models. According to this projection, Sylhet will again have the highest rainfall (27.78 mm), followed by Barishal (23.34 mm), while Rangpur will record the lowest (10.42 mm).

Table 4
Summary of February month average total precipitation of 1970 to 2000, 2010 to 2018 and forecasted 2050 (By RCP model 2.6, 4.5, 6.0 and 8.5)

Division	Average Precipitation (mm) 1970 to 2000	Average Precipitation (mm) 2010 to 2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050 (RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Barishal	28.07	15.36	19.62	25.86	23.8	23.34	23.15	7.79
Chattogram	18.27	10.02	14.85	19.75	17.62	18.19	17.60	7.58
Dhaka	22.07	14.14	17.88	21.75	19.76	20.5	19.97	5.83
Khulna	26.58	15.74	16.13	19.82	18.33	18.25	18.13	2.39
Mymensingh	15.07	10.97	14.47	17.89	16.47	16.84	16.42	5.45
Rajshahi	16.13	12.25	14.40	16.75	15.39	15.84	15.59	3.34
Rangpur	11.85	11.94	9.51	11.07	10.33	10.42	10.33	-1.61
Sylhet	27.44	18.01	22.35	29.22	26.92	27.78	26.57	8.56

3.3. Precipitation of March

Table 5 shows the average precipitation for March between 1970 and 2000 in Bangladesh. The northeastern region experienced the highest rainfall. Central Bangladesh (north and south) received less rainfall, while the lowest was recorded in the northwest, followed by the southeast. Division-wise analysis indicates that Sylhet had the highest rainfall (106.28 mm), followed by Dhaka (49.99 mm), while Rajshahi had the lowest (24.16 mm) and the highest rainfall from 2010-2018 was in the northeastern region, while central Bangladesh had low rainfall. The lowest values were recorded in the northwest, followed by the southeast. Division-wise analysis for this period shows that Sylhet had the highest precipitation (84.58 mm), while Rajshahi had the lowest (20.77 mm).

The March precipitation forecast for 2050 under the RCP 2.6 scenario shows that the northeastern region is projected to have the highest rainfall, while central areas will experience moderate precipitation. The lowest levels will occur in the northwest, followed by the southeast. Division-wise analysis indicates Sylhet will receive the highest rainfall (101.82 mm), while Rajshahi will have the lowest (25.67 mm).

It also describes the March precipitation projection under the RCP 4.5 scenario. The overall distribution is very similar to the RCP 2.6 projection. The results indicate Sylhet will again be the wettest division (97.88 mm), and Rajshahi the driest (25.29 mm) by 2050.

Table 5 also shows the March precipitation forecast under the RCP 6.0 scenario. The rainfall pattern is again comparable to the RCP 2.6 and RCP 4.5 models. According to this projection, Sylhet will record the highest rainfall (116.66 mm), while Rangpur (27.27 mm) and Rajshahi (27.73 mm) will have the lowest.

Under the RCP 8.5 scenario, the pattern is nearly the same as those of RCP 2.6, 4.5, and 6.0. By 2050, Sylhet will again have the highest rainfall (103.43 mm), while Rangpur will remain the driest division (24.39 mm).

Table 5

Summary of the March month average total precipitation of 1970 to 2000, 2010 to 2018 and forecasted 2050 (By RCP model 2.6, 4.5, 6.0 and 8.5)

Division	Average Precipitation (mm) 1970 to 2000	Average Precipitation (mm) 2010 to 2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050 (RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Barishal	48.21	34.91	40.68	43.96	46.95	41.45	43.26	8.35
Chattogram	48.57	37.8	44.79	48.18	51.13	45.47	47.39	9.59
Dhaka	49.99	36.79	48.84	48.50	55.84	50.75	50.98	14.19
Khulna	38.76	26.76	31.75	32.73	36.17	32.6	33.31	6.55
Mymensingh	45.12	37.68	51.33	49.48	57.07	51.12	52.25	14.57
Rajshahi	24.16	20.77	25.67	25.29	27.73	25.41	26.03	5.26
Rangpur	25.41	25.65	26.56	25.53	27.27	24.39	25.94	0.29
Sylhet	106.28	84.58	101.82	97.88	116.66	103.43	104.95	20.37

3.4. Precipitation of April

Table 6 presents the average precipitation for April in Bangladesh during the period 1970 to 2000. The northeastern part of the country recorded the highest rainfall, while central Bangladesh experienced moderate to low precipitation. The western part showed the lowest rainfall during this period. Division-level analysis for April between 1970 and 2000 indicates that Sylhet received the highest average precipitation (264.85 mm), whereas Rajshahi had the lowest (56.28 mm).

For April precipitation averages for 2010 to 2018 in Bangladesh, the northeastern part recorded the highest rainfall, while the central and southeastern areas had moderate to low precipitation, and the western side experienced the lowest. A division-wise breakdown shows that Sylhet had the highest precipitation (307.28 mm), while Rajshahi was the lowest with 62.6 mm on average. It is also noteworthy that Mymensingh experienced slightly more rainfall compared to earlier years, while Dhaka and Chattogram showed a slight decline.

Table 6 also indicates the projected average precipitation for April in Bangladesh under the RCP 2.6 scenario for 2050. The northeastern region is expected to receive the most rainfall, while central and southeastern parts will have lower to moderate levels. The northwestern and southwestern regions will experience the least precipitation. Division-wise forecasts under RCP 2.6 show Sylhet with the highest rainfall (287.95 mm) and Rajshahi with the lowest (65.41 mm).

For April precipitation projection under RCP 4.5 for 2050, the northeastern part will again have the highest rainfall, while the central and southeastern regions will receive relatively low amounts, and the northwestern and southwestern regions will remain the driest. According to this model, Sylhet is expected to have the highest rainfall (259.61 mm), and Rajshahi the lowest (51.3 mm).

The overall rainfall distribution under the RCP 6.0 scenario appears almost identical to that of the RCP 2.6 model. Division-level data reveal Sylhet as the highest with 264.2 mm, while Rajshahi remains the lowest with 54.55 mm in 2050. And under the RCP 8.5 scenario, the rainfall pattern is very similar to the RCP 4.5 model. Value from the table confirms that Sylhet will again receive the highest rainfall (276.59 mm), while Rajshahi will continue to record the lowest (51.81 mm), consistent with the other RCP scenarios.

Table 6
Summary of April month average total precipitation of 1970 to 2000, 2010 to 2018 and forecasted 2050 (By RCP model 2.6, 4.5, 6.0 and 8.5)

Division	Average Precipitation (mm) 1970-2000	Average Precipitation (mm) 2010-2018	Precipitation (mm) 2050 (RCP 2.6)	Precipitation (mm) 2050 (RCP 4.5)	Precipitation (mm) 2050 (RCP 6.0)	Precipitation (mm) 2050 (RCP 8.5)	Average of Precipitation (mm) 2050 (RCP 2.6, 4.5, 6.0 and 8.5)	Average of Precipitation (mm) 2050 to 2010-2018
Barishal	105.46	116.82	104.16	90.95	97.44	92.13	96.17	-20.65
Chattogram	128.83	143.08	131.12	112.53	115.7	119.87	119.80	-23.28
Dhaka	129.52	147.92	137.22	112.66	119.44	120.55	122.47	-25.45
Khulna	74.18	81.18	74.38	62.37	67.94	64.49	67.29	-13.89
Mymensingh	117.09	133.57	145.07	123.91	127.34	127.95	131.07	-2.50
Rajshahi	56.28	62.6	65.41	51.3	54.55	51.81	55.77	-6.83
Rangpur	77	82.27	88.23	73.97	76.59	71.52	77.58	-4.69
Sylhet	264.85	307.28	287.95	259.61	264.2	276.59	272.09	-35.19

3.5. Trend of average precipitation across divisions

The analysis of average precipitation trends across Bangladesh's divisions in figure 3 shows the seasonal and spatial variations from the past period (1970–2000) through the recent decade (2010–2018) and into the projected climate of 2050. During the month of January, it shows the stable dry-season conditions with minor differences between periods. Slight increases are observed in the 2050 projections, particularly in Sylhet, Khulna, and Mymensingh. In February, precipitation rises moderately, and future values remain higher than the recent decade but comparable to the historical baseline. Divisions such as Khulna, Sylhet, and Barishal exhibit the most noticeable increases, suggesting early pre-monsoon intensification. In March, rainfall increases significantly across the country, and Sylhet shows the peak for all periods, reflecting its strong convective activity during the pre-monsoon season. April records the highest rainfall among the four months, with a sharp peak in Sylhet in recent study period exceeding 300 mm historically. However, unlike the earlier months, most divisions show slight reductions in April rainfall in 2050 compared to 2010–2018, indicating a possible shift or delay in the peak pre-monsoon rainfall pattern.

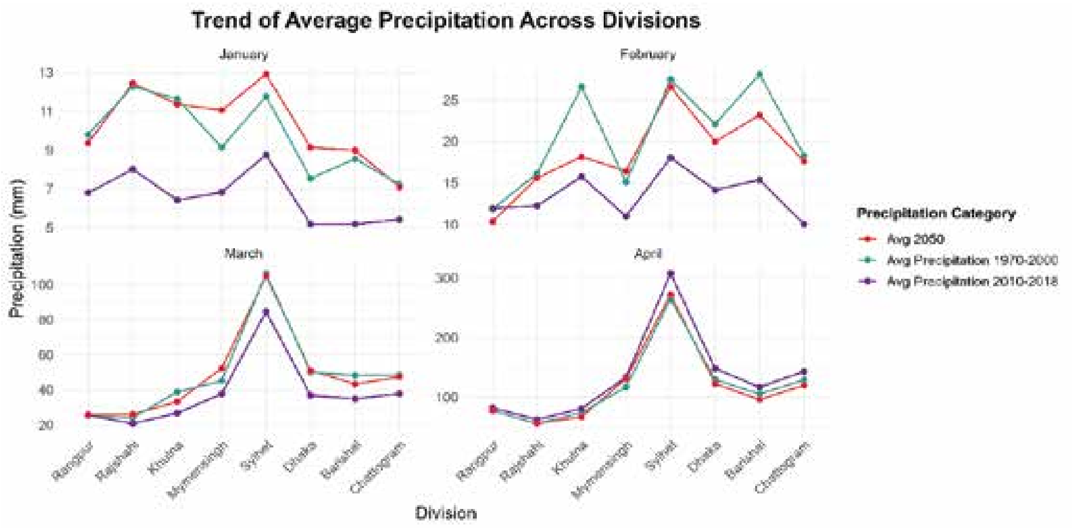

Fig. 3. Trend of average precipitation across divisions.

3.6. Precipitation trend for several RCP models projection

The projected precipitation patterns under all four RCP scenarios in figure 4 show a consistent trend across Bangladesh. April receives the highest rainfall in every scenario, with a sharp peak in Sylhet, followed by Mymensingh and Chattogram. In contrast, January, February, and March show relatively low rainfall across all divisions, with only moderate increases in February and March. The overall spatial pattern remains stable regardless of the emission scenario: Sylhet is consistently the wettest region, while Rajshahi and Rangpur remain the driest. Differences between RCP 2.6, 4.5, 6.0, and 8.5 are small for the early months but slightly more pronounced in April, where higher-emission scenarios show marginally higher rainfall. Overall, April rainfall is the most dominant and sensitive to climate change across all divisions.

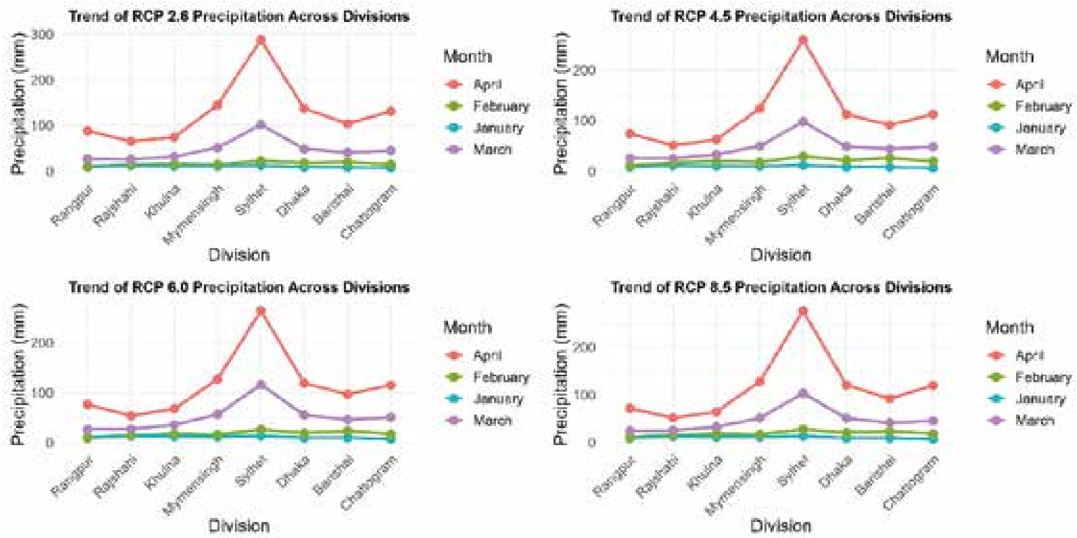

Fig. 4. Precipitation trend for several RCP models projection.

4. Discussion

As the climate continues to change, forecasting future climatic conditions becomes critical in mitigating its impacts and ensuring food security in Bangladesh. Projecting future precipitation patterns is essential for designing effective adaptation strategies, particularly in agriculture. This study aimed to forecast precipitation scenarios for the months of January to April in 2050, at divisional levels, to enhance the understanding of regional climatic variations. The precipitation projections derived from CMIP5 GCMs were compared with observed historical and current precipitation trends to assess potential future changes.

The findings of the study reveal significant regional and temporal variations in precipitation patterns across Bangladesh from January to April. In January, historical data from 1970 to 2000 and 2010 to 2018, along with projections for 2050, indicate that Sylhet historically received the highest precipitation, while Dhaka had the lowest. Bari et al. (2016) found that Sylhet station recorded maximum decrement in monsoon rainfall and minimum in Mymensingh. By 2050, all divisions are expected to see an increase in precipitation, with Sylhet and Rajshahi continuing to receive the most, while Chattogram remains the driest. In February, the highest precipitation during 1970-2000 was recorded in Barishal followed by Sylhet and Khulna, while Chattogram had the lowest. From 2010 to 2018, Sylhet maintained its position as the wettest division, and by 2050, precipitation is projected to increase across most divisions, with Sylhet receiving the highest, and Rangpur the lowest. In March, Sylhet continued to experience the highest rainfall across all periods, with projections for 2050 showing increased precipitation, particularly in Sylhet, Dhaka, and Mymensingh. The April data revealed that Sylhet had the highest precipitation from 1970 to 2000 and 2010 to 2018, with Rajshahi recording the lowest. By 2050, however, a decrease in precipitation is forecasted for most divisions, including a reduction in Sylhet's precipitation, though it will still remain the wettest region. These trends highlight distinct regional shifts and increasing variability in precipitation patterns across the months. In a study conducted by Aziz et al. (2023) reveals that the Mymensingh division will experience a dramatic increase in precipitation along with Sylhet, and Rajshahi will also see some rise in precipitation in mid-century (2040–2060).

A comparative assessment across the RCP scenarios (2.6, 4.5, 6.0, and 8.5) reveals that while the overall spatial pattern of precipitation remains similar, the magnitude of change varies slightly. Under RCP 8.5, precipitation tends to increase marginally more in January–March and shows a sharper decline in April compared to RCP 4.5. These findings suggest that while the direction of change is consistent across emission pathways, the intensity of projected precipitation shifts is influenced by the severity of greenhouse gas concentration scenarios. Similar result is shown from the study of Rahman et al. (2019), Hossain et al. (2020) and Saim et al. (2021).

The Boro season in Bangladesh is traditionally characterized by relatively dry conditions, with precipitation playing a pivotal role in determining agricultural productivity. Recent observations have revealed notable spatial variations in rainfall, with the eastern regions receiving higher precipitation and the northwestern areas experiencing significantly lower rainfall during this period (Aziz et al., 2021). These regional disparities are primarily influenced by the country's topography and prevailing climate patterns. As such, the amount and distribution of precipitation during the Boro season are critical factors for agricultural planning and water resource management.

Looking ahead, future projections indicate an overall increase in precipitation during the Boro season, except for the month of April, which is expected to experience a decrease (Islam et al., 2022; Ta et al., 2022). This trend is supported by multiple climate models, including those from CMIP5 and CMIP6, which forecast higher precipitation levels in the coming decades. Despite the overall increase in precipitation, the spatial distribution of rainfall is expected to remain largely unchanged, with the eastern regions continuing to receive the highest levels of precipitation, while the northwestern region remains the driest (Kamruzzaman et al., 2019). This enduring spatial pattern is significant for agricultural and water management strategies, as it highlights the necessity for region-specific measures to address water availability and crop management challenges.

From a seasonal perspective, while the Boro season spans the dry winter months and the transitional period leading into the monsoon, projections suggest that the monsoon season will experience the most substantial increase in precipitation. The result is similar to the findings of Aadrita & Jahan (2021) and Fahad et al. (2018). This could lead to more frequent and intense rainfall events, raising concerns regarding the potential for flooding and waterlogging, particularly in the eastern and northeastern regions, which are already prone to heavy rainfall (Ahmed et al., 2017; Kamruzzaman et al., 2019). In contrast, the dry winter months are projected to experience reduced rainfall, which may exacerbate drought conditions in the northwestern regions, which are already susceptible to such extremes. In a study, Rajib et al. (2011) found that Percentage of precipitation increment is expected to be quite lower for dry and pre-monsoon months compared to the monsoon season. These projections underscore the importance of developing targeted water management strategies to mitigate the risks associated with both flooding and drought.

Additionally, rising temperatures, particularly in the northwest and south-central regions, are likely to further complicate agricultural practices by altering evapotranspiration rates and soil moisture conditions (Ahmed et al., 2017). Moreover, large-scale climate phenomena such as the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) are recognized for their influence on Bangladesh's precipitation patterns. Research indicates that the IOD has a more substantial teleconnection with Bangladesh's monsoon precipitation compared to ENSO, suggesting that future shifts in IOD patterns could have significant implications for the Boro season (Ahmed et al., 2017).

Projected rainfall changes during the Boro season have clear management implications. Slight increases in January–March may reduce irrigation needs in wetter divisions like Sylhet, while drier regions such as Rajshahi and Rangpur will still require intensive irrigation. However, early-season rainfall could raise waterlogging risks in poorly drained fields, demanding better drainage and disease control. The expected April decline is critical for Boro rice flowering, making precise irrigation scheduling essential to prevent yield loss. These trends call for region-specific strategies, including efficient irrigation systems, rainwater harvesting, and climate-resilient crop varieties.

5. Conclusion

This research analyzed the historical and present precipitation conditions during the Boro season in Bangladesh and projected average rainfall for 2050 using multiple Global Climate Models (GCMs) and Representative Concentration Pathways (RCPs).

January shows low rainfall across all divisions with only small changes over time, and Sylhet records the highest values. In February, rainfall increases slightly, with Sylhet consistently highest and Rangpur lowest. March shows a significant rise in precipitation, especially in Sylhet. April has the highest rainfall overall, dominated by a peak in Sylhet, though most divisions show a slight projected decline compared to recent years. Overall, Sylhet remains the wettest division across all months, largely due to its proximity to the Meghalaya Plateau and enhanced orographic rainfall from moist southwesterly monsoon flows, while Rajshahi and Rangpur remain the driest divisions because of their inland location, distance from major moisture sources, and comparatively weaker monsoon influence. Although the various RCP models produce slightly different trends, the differences are not significant enough to alter the overall conclusions. These results are important for developing agricultural strategies under climate change. The projections can support climate-smart farming practices, guide technological innovations, and help secure future food production. This study also emphasizes the importance of extending research to other climatic factors such as maximum and minimum temperatures, humidity, and sunshine hours, as further investigation is needed to predict future climatic conditions in Bangladesh.

Policy Recommendation

Based on the projected precipitation patterns during the Boro season (January–April) for 2050, several targeted policy interventions are recommended to enhance climate-resilient agricultural planning in Bangladesh

First, region-specific water management policies are essential. The persistent low rainfall projected for the northwestern divisions, particularly Rajshahi and Rangpur, indicates continued dependence on groundwater irrigation. Policymakers should prioritize investment in efficient irrigation technologies (such as drip and sprinkler systems), surface water storage, and rainwater harvesting to reduce groundwater depletion and drought vulnerability in these regions.

Second, in high-precipitation regions such as Sylhet, where rainfall remains consistently higher even during the Boro season, policies should focus on improving drainage infrastructure and field-level water management. Although increased rainfall may reduce irrigation demand, even modest increases during sensitive crop stages can raise the risk of waterlogging and disease. Strengthening canal maintenance, promoting raised-bed cultivation, and supporting drainage-sensitive crop varieties can mitigate these risks.

Third, the GIS-based precipitation maps developed in this study should be institutionalized within national planning frameworks. These spatial tools can support evidence-based crop zoning, optimize regional cropping calendars, and guide the allocation of water and agricultural inputs. Integrating these maps into existing platforms such as early warning systems and weather-based advisory services will improve preparedness for climate variability.

Finally, long-term agricultural policy should emphasize climate-resilient crop development and farmer capacity building. Investment in drought-tolerant and waterlogging-tolerant crop varieties, combined with farmer training on climate-smart practices, will strengthen adaptive capacity across diverse agro-climatic zones. Coordinated action among government agencies, research institutions, and local stakeholders is crucial to ensure sustainable food production under changing precipitation regimes.

Author's Contributions

N M F Rahman conceived and designed the study, developed the methodological framework, conducted the analysis, and prepared the initial draft of the manuscript. M A Aziz contributed to study design, performed statistical analyses, and assisted in interpreting the results. Rokib Ahmed contributed to data curation, literature review, and preparation of supporting materials. ABM Z Hossain, M A Siddique, M C Rahman, S A I Nihad, M A Qayum, M A A Mamun, and M I Hossain assisted in manuscript editing, visualization, and provided critical revisions. M R Islam provided senior guidance, critical feedback, overall supervision, and final approval of the manuscript.

References

Aadrita, M. M., & Jahan, N. (2021, December). Projection of precipitation and temperature extremes over Bangladesh from CMIP6 SSP-RCP scenarios. In AGU Fall Meeting Abstracts (Vol. 2021, pp. H41D-08).

Adopted Intergovernmental Panel on Climate Change (IPCC). (2014). Climate change 2014: Synthesis report. Geneva, Switzerland: IPCC.

Ahmed, M. K., Alam, M. S., Yousuf, A. H., & Islam, M. M. (2017). A long-term trend in precipitation of different spatial regions of Bangladesh and its teleconnections with El Niño/Southern Oscillation and Indian Ocean Dipole. Theoretical and Applied Climatology, 129(1–2), 473–486.

Ali, S., Liu, Y., Ishaq, M., Shah, T., Ilyas, A., & Din, I. U. (2017). Climate change and its impact on the yield of major food crops: Evidence from Pakistan. Foods, 6(6), 39. https://doi.org/10.3390/foods6060039

Amin, M., Zhang, J., & Yang, M. (2015). Effects of climate change on the yield and cropping area of major food crops: A case of Bangladesh. Sustainability, 7(1), 898–915. https://doi.org/10.3390/su7010898

Aziz, M. A., Hossain, A. B. M. Z., Moniruzzaman, M., et al. (2021). Mapping of agricultural drought in Bangladesh using geographic information system (GIS). Earth Systems and Environment.

Aziz, M. A., Shohan, H. U. S., Rahman, N. M. F., Rahman, M. C., Nihad, S. A. I., Hassan, S. Q., ... & Rukshanara, Z. (2023). Projection of future precipitation in Bangladesh at Kharif-II season using geospatial techniques. Earth Systems and Environment, 7(1), 255-266.

Bangladesh Economic Review (BER). (2020). Bangladesh Economic Review 2020. Ministry of Finance, Government of the People's Republic of Bangladesh.

Bari, S. H., Rahman, M. T. U., Hoque, M. A., & Hussain, M. M. (2016). Analysis of seasonal and annual rainfall trends in the northern region of Bangladesh. Atmospheric Research, 176, 148-158.

Bosu, H., Rashid, T., Mannan, A., & Meandad, J. (2020). Climate change analysis for Bangladesh using CMIP5 models. The Dhaka University Journal of Earth and Environmental Sciences, 9(1), 1–12.

Chowdhury, M. M. I., Rahman, S. M., Abubakar, I. R., Aina, Y. A., Hasan, M. A., & Khondaker, A. N. (2020). A review of policies and initiatives for climate change mitigation and environmental sustainability in Bangladesh. Environment, Development & Sustainability.

Cole, M. (2021). Climate change, the fourth industrial revolution and public pedagogies: The case for ecosocialism. Routledge.

DAS, L. C., Mohiul Islam, A. S. M., AKTAR, S., & SULTANA, F. (2024). Climate change challenges in Bangladesh. International Journal of Big Data Mining for Global Warming, 6(01), 2430001.

Fahad, M. G., Islam, A. K. M. S., Nazari, R., Hasan, M. A., Islam, G. M. T., & Bala, S. K. (2018). Regional changes of precipitation and temperature over Bangladesh using bias-corrected multi-model ensemble projections considering high-emission pathways. International Journal of Climatology, 38(4), 1634–1648. https://doi.org/10.1002/joc.5290

Farhana, Z., Rahman, M. M., Rahman, N. M. F., Hossain, M., & Uddin, M. T. (2022). Discovering the Change of Major Climatic Elements in Bangladesh: a Statistical Application of Trends, Growth and Variability Analysis. Mausam, 73(2), 441-446.

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37(12), 4302–4315. https://doi.org/10.1002/joc.5086

Firon, N., Shaked, R., Peet, M. M., et al. (2006). Pollen grains of heat-tolerant tomato cultivars retain higher carbohydrate concentration under heat stress conditions. Scientia Horticulturae.

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., ... & Rummukainen, M. (2014). Evaluation of climate models. In Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 741–866). Cambridge University Press.

Fujino, J., Nair, R., Kainuma, M., Masui, T., & Matsuoka, Y. (2006). Multi-gas mitigation analysis on stabilization scenarios using AIM global model. The Energy Journal, Special Issue 3.

GISGeography. (2021, May 8). Vector vs raster: What's the difference between GIS spatial data types? GISGeography. https://gisgeography.com/spatial-data-types-vector-raster/

Hasan, J., Kulsum, U., Rahman, N. F., Farhat, T., & Siddique, A. (2015). Hybrid rice parental lines development utilizing different rice germplasms. Advances in Environmental Biology, 24-30.

Hausfather, Z., & Peters, G. P. (2020). Emissions–the 'business as usual'story is misleading. Nature, 577(7792), 618-620.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Guillén Bolaños, T., Bindi, M., Brown, S., ... & Zhou, G. (2019). The human imperative of stabilizing global climate change at 1.5 C. Science, 365(6459), eaaw6974.

Hossain, M. I., Rahman, N. M. F., Kabir, M. S., Siddique, M. A. B., & Tareq, M. (2015). Development and validation of producer and consumer preference models for rice varieties in Bangladesh. Bangladesh Rice Journal, 19(1), 63-71.

Hossain, S. S., Mingying, M., & Delin, H. (2020). Climate Change in Bangladesh: Evidence from temperature, precipitation, and rainfall. International Journal of Arts Humanities and Social Sciences Studies, 5(10), 80-88.

International Food Policy Research Institute (IFPRI). (2010). IFPRI Annual Report 2009. Washington, D.C. https://doi.org/10.2499/9780896297852

Islam, H. T., Islam, A. R. M. T., Shahid, S., Alam, G. M., Biswas, J. C., Rahman, M. M., Roy, D. K., & Kamruzzaman, M. (2022). Future precipitation projection in Bangladesh using SimCLIM climate model: A multi-model ensemble approach. International Journal of Climatology, 42(13), 6716–6740.

Islam, M. A., Hasanuzzaman, M. and Islam, A. R. M. T. 2022. Existing Rainfall Patterns and Its Impact of Rice Production in Rangpur District of Bangladesh. Bangladesh J. Environ. Sci., 42:7-12

Islam, M. A., Rahman, M. C., Sarkar, M. A. R., & Siddique, M. A. B. (2019). Assessing impact of BRRI-released modern rice varieties adoption on farmers' welfare in Bangladesh: Application of panel treatment effect model. Bangladesh Rice Journal, 23(1), 1–11.

Kamruzzaman, M., Jang, M. W., Cho, J., & Hwang, S. (2019). Future changes in precipitation and drought characteristics over Bangladesh under CMIP5 climatological projections. Water, 11(11), 2219.

Kulsum, M. U., Hasan, M. J., Hossain, M. I., & Rahman, N. M. F. (2014). Stability for BRRI developed promising hybrid rice for yield and it's related traits.

Miao, C., Duan, Q., Sun, Q., Huang, Y., Kong, D., Yang, T., ... & Gong, W. (2014). Assessment of CMIP5 climate models and projected temperature changes over Northern Eurasia. Environmental Research Letters, 9(5), 055007. https://doi.org/10.1088/1748-9326/9/5/055007

Moss, R. H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J. A., ... & Zurek, M. (2008). Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies.

Odunmorayo, M. T., Alani, B. O., & Adefisan, E. A. (2025). Projected change in occurrence and severity of heatwaves over West Africa as simulated by CMIP6 models. Journal of Disaster Science and Management, 1(1), 16.

Parker, L., Bourgoin, C., Martinez-Valle, A., & Läderach, P. (2019). Vulnerability of the agricultural sector to climate change: The development of a pan-tropical climate risk vulnerability assessment to inform sub-national decision making. PLoS ONE, 14(3), e0213641. https://doi.org/10.1371/journal.pone.0213641

Prodhan, A. Z. M. S., Islam, M. S., Islam, M. M., Haque, M. N., & Islam, M. (2018). Effect of soil and environment on winter vegetables production. MOJ Food Processing & Technology, 6(4), 384–389.

Rahaman, A. Z. (2019). Study on climate anomalies of Bangladesh using statistically downscaled climate projections for representative concentration pathways (RCPs) of IPCC fifth assessment report.

Rahman, M. A., Kang, S. C., Nagabhatla, N., & Macnee, R. (2017). Impacts of temperature and rainfall variation on rice productivity in major ecosystems of Bangladesh. Agriculture & Food Security.

Rahman, M. C., Miah, T. H., & Rashid, M. H. (2015). Effects of controlling saline water intrusion in an empoldered area of Bangladesh. In Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices Conference Proceedings (p. 89). CGIAR Challenge Program on Water and Food (CPWF).

Rahman, M. C., Pede, V., Balie, J., Pabuayon, I. M., Yorobe, J. M., & Mohanty, S. (2020). Assessing the market power of millers and wholesalers in the Bangladesh rice sector. Journal of Agribusiness in Developing and Emerging Economies, 11(3), 280-295.

Rahman, M. M. (2021). Achieving Sustainable Development Goals of Agenda 2030 in Bangladesh: The crossroad of the governance and performance. Public Administration and Policy, 24(2), 195–211.

Rahman, M. M., Ferdousi, N., Abdullah, S. M. A., Kusunoki, S., & Islam, A. (2019). Recent climate simulation over SAARC region including Bangladesh using high-resolution AGCM. Asia-Pacific Journal of Atmospheric Sciences, 55(2), 115–134.

Rahman, N., Rahman, M., Baten, M., Hossain, M., Hassan, S., Ahmed, R., ... & Kabir, M. (2021). Weather forecast-based rice advisory services in Bangladesh. Bangladesh Rice Journal, 25(1), 51–74. https://doi.org/10.3329/brj.v25i1.55179

Rahman, N. M. F., Asadullah, M., Hossain, M. S., Uddin, M. J., Haque, N., Rashid, M. B., ... & Baten, M. A. (2025). Spatiotemporal trends and machine learning-based prediction of temperature variability during the T. Aman rice-growing season in Bangladesh. Scientific Reports, 15(1), 44883.

Rahman, N. M. F., Haque, N., Asadullah, M., Hossain, A. B. M. Z., Hossain, M. S., Uddin, M. J., ... & Baten, M. A. (2026). Machine learning-based temperature prediction across diverse ecosystems for the Boro Season in Bangladesh. Scientific Reports.

Rajib, M. A., Rahman, M. M., Islam, A. S., & McBean, E. A. (2011). Analyzing the future monthly precipitation pattern in Bangladesh from multi-model projections using both GCM and RCM. In World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability (pp. 3843–3851). American Society of Civil Engineers. https://doi.org/10.1061/41173(414)402

Rashid, M., & Yasmeen, R. (2018). Cold injury and flash flood damage in Boro rice cultivation in Bangladesh: A review. Bangladesh Rice Journal, 21(1). https://doi.org/10.3329/brj.v21i1.37360

Saim, A. A., & Rahman, S. H. (2021). Impacts of Climate Change on Dry Season Flow of Gorai River, Bangladesh Using SWAT Model. Bangladesh Journal of Environmental Research, 12, 20-36.

Sarker, M. A. R., Alam, K. and Gow, J. 2012. Exploring the Relationship between Climate Change and Rice Yield in Bangladesh: An Analysis of Time Series Data, Agric. Sys., 112:11-16.

Sharmin, S., Mitra, S., & Rashid, M. H.-A. (2018). Production, yield and area growth of major winter vegetables of Bangladesh. Journal of the Bangladesh Agricultural University, 16(3). https://doi.org/10.3329/jbau.v16i3.39447

Shozib, H. B., Siddiquee, M. A., Rahman, N. M. F., Mamun, M. A. A., Sarkar, M. A. R., Rabbi, S. M. H. A., ... & Kabir, M. S. (2020). Grain quality research of rice for ensuring nutritional food security. Bangladesh Rice Journal, 24(2), 103-117.

Ta, A. T. M., Islam, M. R., & Imran, H. M. (2022). Future precipitation scenario in Bangladesh: A CMIP-6 based analysis. Research Square.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), 485–498.

Team, C. W., Pachauri, R. K., & Meyer, L. (Eds.). (2015). Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.

Tomás, D., Rodrigues, J. C., Viegas, W., & Silva, M. (2020). Assessment of high temperature effects on grain yield and composition in bread wheat commercial varieties. Agronomy, 10(4), 409. https://doi.org/10.3390/agronomy10040499

Trenberth, K. E. (2011). Changes in precipitation with climate change. Climate Research, 47(1–2), 123–138. https://doi.org/10.3354/cr00953

Yang, T., Hao, X., Shao, Q., Xu, C. Y., Zhao, C., Chen, X., & Wang, W. (2012). Multi-model ensemble projections in temperature and precipitation extremes of the Tibetan Plateau in the 21st century. Global and Planetary Change, 80, 1–13. https://doi.org/10.1016/j.gloplacha.2011.08.006

Yu, W., Alam, M., Hassan, A., Khan, A. S., Ruane, A., Rosenzweig, C., ... & Thurlow, J. (2010). Climate change risks and food security in Bangladesh. Routledge.

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Head Rice Recovery, Comparative Advantage, and International Competitiveness of BRRI dhan50 Aromatic Rice in Bangladesh: Evidence from Policy Analysis Matrix

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ABSTRACT

This study evaluates the comparative advantage and export potential of BRRI dhan50, a modern aromatic rice variety in Bangladesh, using the Policy Analysis Matrix (PAM) framework. It addresses a key empirical paradox in the rice economy, where conventional financial indicators suggest limited profitability, while efficiency-based measures reveal positive economic returns at both private and social prices. Primary data were collected from 160 randomly selected farmers in Jashore district during the 2021-22 Boro season. The results indicate that at a 56% head rice recovery (HRR), achievable through modern rubber huller milling, BRRI dhan50 demonstrates strong financial performance and a clear comparative advantage under both import and export parity conditions. However, when HRR declines to 52%, reflecting conventional milling practices, the variety retains comparative advantage only under import parity, while export competitiveness is lost, underscoring the critical role of post-harvest processing efficiency in determining international competitiveness. Sensitivity analysis further confirms that export competitiveness is highly vulnerable to reductions in milling efficiency, with DRC exceeding unity at lower HRR levels. Policy indicators (NPC = 2.38; EPC = 2.86) reveal substantial price distortions and policy-induced protection, while a positive Profitability Coefficient (PC = 5.12) indicates net transfers in favor of producers. Overall, BRRI dhan50 exhibits strong potential as a value-added aromatic rice for import substitution and conditional export competitiveness, contingent on improved milling performance and institutional support. The findings emphasize that enhancing head rice recovery, strengthening post-harvest management, and improving quality assurance systems are essential for sustaining export competitiveness. Long-term competitiveness will depend on investments in modern processing infrastructure, value-chain development, research and development, export diversification, logistics efficiency, and national branding strategies for Bangladeshi aromatic rice in global markets.

1. Introduction

Rice serves as the principal staple for more than half of the global population, providing over 20% of daily caloric intake worldwide (Tama et al., 2018). Consumption is particularly high in Asia, where per capita intake frequently exceeds 100 kg annually. While most rice is consumed domestically, international trade has grown significantly in recent years. A limited number of exporting countries now account for the majority of global supply, creating a concentrated market structure that increases

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susceptibility to supply disruptions and price volatility (Tama et al., 2018).

Aromatic rice constitutes a premium niche in the global market due to its unique fragrance and strong consumer preference. In Bangladesh, these varieties command prices that are typically two to three times higher than those of non-aromatic rice and are widely associated with cultural and religious occasions. Since the early 1990s, the country has exported small quantities of traditional aromatic varieties such as Kalijira and Chinigura mainly to Middle East and selected European markets, largely to meet the demand of expatriate communities (Rahman, 2000; Tama et al., 2018).

To enhance commercial prospects, Bangladesh has developed and released modern aromatic rice varieties through breeding programs led by the Bangladesh Rice Research Institute (Table 1). Among these improved lines, BRRI dhan50 (Banglamoti) stands out for its characteristics that are especially attractive to international consumers.

Table 1

Modern aromatic rice varieties in Bangladesh.

Variety	Year of release	Season	Gain type	Yield (ton/ha)
BR5	1976	T. Aman	Oval	3.0
BRRI dhan34	1997	T. Aman	Short bold	3.5
BRRI dhan37	1998	T. Aman	Medium slender	3.5
BRRI dhan38	1998	T. Aman	Medium slender	3.5
BRRI dhan50	2008	Boro	Long slender	6.0
BRRI dhan70	2015	T. Aman	Long slender	5.0
BRRI dhan90	2019	T. Aman	Short bold	5.0
Binadhan-9	2012	T. Aman	Long slender	3.8
Binadhan-13	2013	T. Aman	Bold	3.5
Binadhan-18	2015	Boro	Medium bold	7.3

Source: BRRI (2025) and https://bina.gov.bd.

Based on the data presented in Fig. 1, the area coverage of BRRI dhan50 in Bangladesh over a 14-year period shows a distinct lifecycle typical of an adopted particular variety. The timeline begins in the fiscal year 2011-12 with an initial introduction covering just 5.8 thousand hectares. Following this rollout, the variety experienced a rapid and steep adoption phase as farmers quickly expanded its cultivation. By 2013-14, cultivation had surged to 52.7 thousand hectares, and it continued a steady upward trajectory over the next few years, crossing the 74.0 thousand hectare mark by 2015-16.

The variety reached its absolute peak in the fiscal year 2017-18, securing a maximum coverage of 86.5 thousand hectares. Following this peak, BRRI dhan50 entered a brief plateau period, maintaining high coverage at 86.2 thousand hectares in 2018-19 and 84.8 thousand hectares in 2019-20. This period represents the height of its widespread acceptance and market stabilization across the country's rice-growing regions.

After 2019-20, the graph indicates a gradual, multi-year decline in cultivation area. The coverage dropped to 80.4 thousand hectares in 2020-21, and despite a minor, temporary rebound to 81.4 thousand hectares in 2021-22, the downward trend resumed sharply over the following two years. By 2023-24, the area had contracted to its lowest point in a decade at 65.4 thousand hectares, likely due to the introduction of newer, higher-yielding varieties or changing environmental and market dynamics. However, the final year of the dataset, 2024-25, shows a slight recovery to 67.0 thousand hectares, indicating that the variety has settled into a stable, lasting niche within Bangladesh's agricultural landscape.

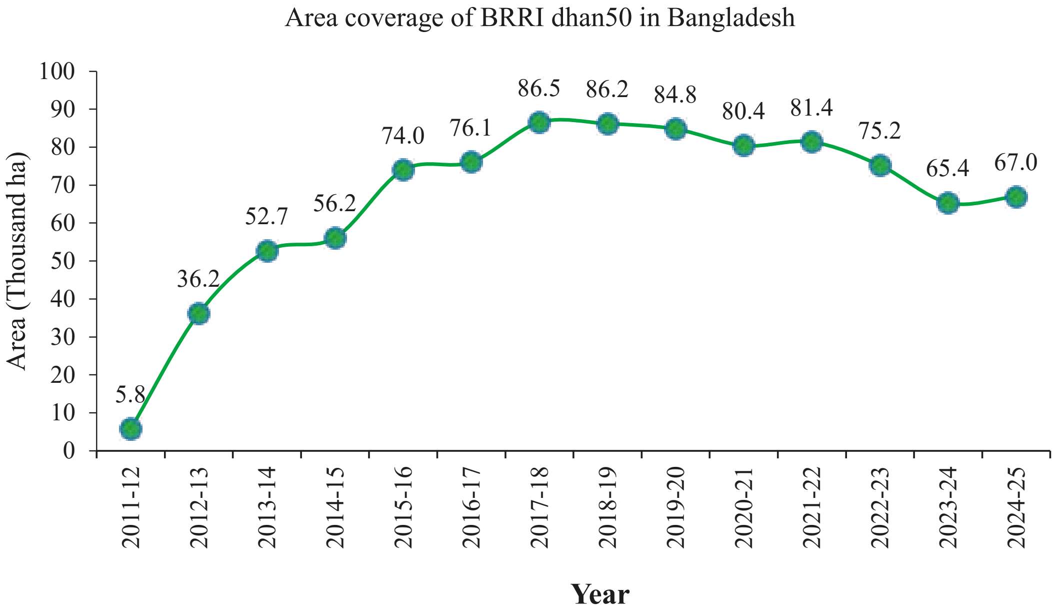

Fig. 1. Adoption of BRRI dhan50 in Bangladesh.
Note: Authors' estimation based on data from the Department of Agriculture Extension (DAE).

Existing empirical literature on Bangladesh's rice sector has predominantly concentrated on traditional aromatic rice varieties cultivated in the Aman season, with a particular emphasis on assessing comparative advantage and international competitiveness using the Domestic Resource Cost (DRC) ratio (Anik & Talukder, 2002; Rashid, 2009; Kazal et al., 2013). These studies have provided important foundational evidence that certain indigenous aromatic rice varieties can be economically viable under existing policy and market conditions. However, this body of work remains limited in scope, as it largely excludes modern high-yielding aromatic rice varieties that have been recently developed and introduced by national breeding programs.

In particular, the export competitiveness of modern aromatic rice varieties such as BRRI dhan50, which is predominantly cultivated in the Boro season, remains underexplored in the existing literature. This is a critical gap, given that varietal improvements, changes in seasonal production systems, and evolving market demand for premium rice types may substantially alter competitiveness outcomes compared to earlier findings based on traditional cultivars. As a result, existing evidence may not adequately reflect the current and potential future export position of Bangladesh's aromatic rice sector.

Unlike previous studies, this research incorporates the head rice recovery ratio (HRR)-a key determinant of milling yield and exportable produce quality that directly affects tradable surplus but has often been overlooked in earlier studies.

To address this gap, this study evaluates the international competitiveness of un-parboil BRRI dhan50 using the Policy Analysis Matrix (PAM) framework, which provides a more comprehensive assessment by simultaneously capturing private profitability, economic efficiency, and policy distortions. Furthermore, the analysis extends beyond conventional tradable input assumptions by incorporating a broader set of input cost structures, thereby improving the precision of economic valuation.

In addition, this study introduces a distinction between observed (actual farmer practices) and technically efficient production scenarios, allowing for a more nuanced evaluation of competitiveness under both current behavioral constraints and potential productivity improvements. This dual approach provides insights into whether farmers can remain competitive not only under existing policy distortions but also under improved efficiency conditions.

Overall, the findings are expected to generate robust empirical evidence to guide policymakers in assessing the feasibility and strategic potential of exporting modern aromatic rice from Bangladesh in an increasingly competitive global rice market.

Objectives of the study

Given the shifting dynamics in Bangladesh's aromatic rice sector, this study addresses existing research gaps through four specific objectives:

1. to evaluate the private and social profitability of cultivating the modern aromatic Boro rice variety, BRRI dhan50, at the farm level.
2. to assess the international competitiveness and comparative advantage of BRRI dhan50 under both import-substitution and export-parity scenarios.
3. to empirically measure the impact of post-harvest milling yield-specifically comparing Head Rice Recovery (HRR) ratios of 56% and 52%, and
4. to measure macroeconomic exchange rate fluctuations on the stability of this comparative advantage using sensitivity analysis.

2. Methodology

2.1. Data and study area

The study is based on cross-sectional primary data gathered during the 2021–22 Boro season from Jashore district, a major production area for BRRI dhan50 aromatic rice. Two Upazilas (Jashore Sadar and Monirampur) were purposively selected, followed by the selection of two Unions each Upazila and two villages from each Union. From village-level farmer lists prepared with support from the Department of Agricultural Extension (DAE), a total of 160 BRRI dhan50 farmers were randomly sampled. Data were collected using a structured interview schedule and standardized procedures to ensure accuracy and consistency.

2.2. Head rice recovery ratio

Head rice recovery ratio (HRR) significantly influences the economic value of aromatic rice, particularly for export markets (Prasanna & Reddy, 2025). In Bangladesh, milling efficiency varies by technology: rubber huller mills recover up to 56% head rice, while engelberg mills recover up to 52% for BRRI dhan50 (Rahman et al., 2011). Both HRR values were incorporated into PAM calculations under import and export parity price scenarios.

2.3. Policy analysis matrix

The Policy Analysis Matrix (PAM), developed by Monke & Pearson (1989), is used to assess private and social profitability and to identify policy-induced distortions in BRRI dhan50 production. The framework distinguishes between tradable and non-tradable inputs and compares market prices with social (efficiency) prices to evaluate comparative and competitive advantage. This study extends the conventional PAM by incorporating a broader set of tradable inputs, including seed, pesticides, machinery, urea, TSP, MoP, gypsum, and ZnSO4, as well as by analyzing both observed and technically efficient production scenarios. This allows a more precise evaluation of cost efficiency, productivity gains, and long-term competitiveness under international market pressure.

Private profitability reflects actual farm-level returns based on market prices, incorporating taxes, subsidies, and policy distortions, and indicates financial viability for producers. In contrast, social profitability uses shadow prices to reflect true economic values, excluding distortions, and measures contribution to national welfare and comparative advantage.

The divergence between private and social profitability reveals policy effects and market imperfections. Higher private than social returns suggest policy protection, while higher social than private returns indicate inefficiencies or disincentives. Rooted in welfare economics and Ricardo's comparative advantage theory, PAM operationalizes these concepts through shadow pricing to evaluate efficiency and policy-induced transfers (Pearson et al., 2003; Monke & Pearson, 1989).

2.4. Sensitivity analysis

Sensitivity analysis is an essential component of Policy Analysis Matrix (PAM) analysis because it evaluates how changes in key economic variables, such as exchange rates, input prices, output prices, taxes, or subsidies, affect profitability, comparative advantage, and policy incentives. Since agricultural markets are highly sensitive to policy and market fluctuations, sensitivity analysis helps determine the stability and reliability of PAM results under alternative economic scenarios. It also identifies whether a production system remains competitive and economically efficient when economic conditions change.

In PAM studies, indicators such as Financial Profitability (FP), Social Profitability (SP), Domestic Resource Cost (DRC), and protection coefficients may vary significantly due to changes in market conditions. Therefore, sensitivity analysis is widely used to assess the robustness of comparative advantage and the effects of policy distortions on domestic production systems. For example, an increase in the exchange rate may raise the economic cost of tradable inputs, reduce social profitability, and weaken comparative advantage, even when private profitability remains stable. Thus, sensitivity analysis provides important guidance for policymakers in designing sustainable agricultural and trade policies. In this study, we set assumption: existing market exchange rate has increased from 1 US$ = 84.80 BDT (base) to 1 US$ = 100 BDT.

The PAM yields indicators that determine whether an agricultural system is competitive and has comparative advantage. The following formulations then assess comparative advantage within the PAM framework.

Table 2

The accounting structure of the Policy Analysis Matrix.

Items	Revenue	Costs		Profit
		Tradable inputs	Non-tradable inputs	
Private	A	B	C	$D_{(1)}$
Social	E	F	G	$H_{(2)}$
Divergences	$I_{(3)}$	$J_{(4)}$	$K_{(5)}$	$L_{(6)}$
(1) Private profits (D = A – B – C)			(2) Social profits (H = E –F – G)	
(3) Output transfers (I = A – E)			(4) Input transfers (J = B – F)	
(5) Factor transfers (K = C –G)			(6) Net transfers (L = I – J – K)	

Source: Monke & Pearson, 1989.

2.5. The domestic resource cost ratios (DRC)

The DRC, which would provide a measure of the level of comparative advantage to be achieved by the selected system as:

$$DRC = \frac{\text{Social costs of non tradable inputs (G)}}{\text{Social revenue (E) - Social cost of tradable inputs (F)}}$$

Decision criteria:

DRC < 1 means that economic activity is economically efficient in the use of domestic resources or that economic activity has a comparative advantage so that domestic fulfilment is more profitable with an increase in domestic production. Domestic resource investment is beneficial to agricultural production's contribution to international revenue and comparative advantage;

DRC > 1 means that economic activity is not economically efficient in the use of domestic resources or that economic activity causes comparative losses.

2.6. Financial cost benefit ratio (FCB)

The FCB is the value of the domestic factors against the difference between the revenue minus tradable inputs.

$$FCB = \frac{\text{Private cost of non tradable inputs (C)}}{\text{Private revenue (A)-Private cost of tradable inputs (B)}}$$

Decision criteria:

FCB < 1 it means that the system is profitable;

FCB > 1 it means that the system utilizes more value of domestic factors than the value added, then the system is not profitable;

FCB = 1 means that the economic activity provides a normal profit or the activity is at a break-even point.

2.7. The nominal protection coefficient (NPC)

The NPC shows the level of protection for the tradable output by looking at the ratio of revenue of private prices to revenue at social prices.

$$NPC = \frac{\text{Private revenue (A)}}{\text{Social Revenue (E)}}$$

Decision criteria:

NPC > 1 it indicates that the main output is undervalued at its private price, resulting in a transfer of wealth from the production system to the economy;

NPC < 1 it indicates that the production system benefits from protection.

2.8. The effective protection coefficient (EPC)

The EPC compares the value added at private prices to the value added at social prices. This gives us a combined index of the level of trade distortion on both tradable inputs and outputs and provides a more accurate measure of the level of protection than the NPC.

$$EPC = \frac{\text{Private revenue (A)-Private cost of tradable input (B)}}{\text{Social Revenue (E)-Social cost of tradable inputs (F)}}$$

Decision criteria:

EPC < 1 it means that the system generates less value added at market prices than it would at social prices, i.e., government does not provide effective protection;

EPC > 1 it means that the selected system is protected.

3. Results

3.1. Import parity-based PAM results (HRR = 56%)

The import-parity PAM results shown in Table 3, based on a head rice recovery (HRR) of 56%, indicate that BRRI dhan50 production in Jashore is both competitive and exhibits a clear comparative advantage. At private prices, the Financial Cost-Benefit

(FCB) ratio is estimated at 0.52, which is well below unity. This suggests that farmers are able to cover production costs and generate profits under prevailing market conditions, confirming the financial competitiveness of BRRI dhan50 from the producers' perspective.

At social prices, the Domestic Resource Cost (DRC) ratio is estimated at 0.65, indicating a strong comparative advantage: the domestic resources required to produce BRRI dhan50 are valued at less than the foreign exchange saved through import substitution. The Social Cost-Benefit (SCB) ratio of 0.73 further confirms economic efficiency when inputs are priced at their opportunity cost, as it accounts for both tradable and non-tradable components of production

The Nominal Protection Coefficient (NPC) for output is 2.18, which is greater than unity, indicating that domestic farmgate market prices are substantially higher than world reference (border parity) prices. This reflects a high level of market protection, resulting in an implicit net transfer of wealth from the national economy to the production system. When both output and input policies are considered, the Effective Protection Coefficient (EPC) of 2.55 further confirms that the domestic production system benefits from strong overall policy protection, which inflates net value-added at private prices relative to social efficiency prices. The Profitability Coefficient (PC) of 3.55, along with a positive net transfer of BDT 23,855, further demonstrates that policy interventions generate substantial gains for producers, allowing private profits to significantly exceed true economic profits.

The Producer Subsidy Ratio (PSR) of 0.68 suggests substantial policy support for both outputs and production factors, while the Equivalent Producer Subsidy (EPS) of 0.31 indicates that producers receive support equivalent to 31% of social revenue, with no corresponding offsetting transfers to consumers. Therefore, under an import-parity frame-work, BRRI dhan50 production appears economically efficient and policy-supported, strengthening its potential as a competitive aromatic rice variety for import substitution in Bangladesh.

3.1.1. Sensitivity analysis

Table 3 presents the results of the Policy Analysis Matrix (PAM) indicators for the export potential rice variety, BRRI dhan50, under the existing situation and a sensitivity analysis where the exchange rate increases. The findings indicate that BRRI dhan50 production remains financially and economically viable even after the exchange rate adjustment, although some comparative advantage indicators slightly deteriorate.

The financial profitability (FP) remained unchanged at BDT 33,205 under both the base and sensitivity scenarios. This indicates that farmers' private profits were not directly affected by the increase in the exchange rate. Similarly, the financial cost-benefit ratio (FCB) also remained constant at 0.52, suggesting that the production system is financially efficient because the production costs are substantially lower than the financial returns.

In contrast, the social profitability (SP) declined from BDT 9,349 to BDT 8,082 when the exchange rate increased. This reduction implies that from the perspective of the national economy, the net social gain from producing BRRI dhan50 decreased slightly due to higher economic costs associated with tradable inputs and imported components. Nevertheless, the positive SP values in both cases confirm that the variety still contributes positively to the economy.

The domestic resource cost (DRC) increased slightly from 0.65 to 0.68 under the higher exchange rate scenario. Since the DRC values remain below one, Bangladesh still retains a comparative advantage in producing BRRI dhan50 domestically rather than importing rice. However, the increase in DRC suggests a modest reduction in international competitiveness due to the exchange rate shock. Similarly, the social cost-benefit ratio (SCB) rose from 0.73 to 0.77, indicating a slight decline in economic efficiency, although the values below one still demonstrate that the social benefits exceed the social costs.

The transfer value increased from BDT 23,855 to BDT 25,122, indicating that producers continue to receive substantial policy-induced incentives or market distortions favoring domestic production. The nominal protection coefficient (NPC) remained unchanged at 2.18, implying that domestic output prices are more than twice the corresponding world prices in both situations. This reflects significant market protection for rice producers.

The effective protection coefficient (EPC) increased from 2.55 to 2.67 after the exchange rate increase. This suggests that value-added at private prices became relatively more protected compared to social prices. Likewise, the profitability coefficient (PC) increased from 3.55 to 4.104, indicating that private profitability is substantially higher than social profitability under the distorted market conditions.

Furthermore, the producer subsidy ratio (PSR) increased from 0.68 to 0.717, while the equivalent producer subsidy (EPS) rose from 0.31 to 0.33. These increases imply that producers receive relatively greater implicit support or protection under the higher exchange rate scenario.

Table 3
Results of import parity-based PAM indicators of export potential rice variety considering 56% HRR.

Indicators	Equations	Main Analysis	Sensitivity Analysis
Financial Profitability (FP)	D = A-B-C	33205	33205
Financial Costs-Benefit Ratio (FCB)	C/(A-B)	0.52	0.52
Social Profitability (SP)	H = E-F-G	9349	8082
Domestic Resource cost (DRC)	G/(E-F)	0.65	0.68
Social Costs-Benefit Ratio (SCB)	(F + G)/E	0.73	0.77
Transfer	L = I-J-K	23855	25122
Nominal Protection Coefficient (NPC)	A/E	2.18	2.18
Effective Protection Coefficient (EPC)	(A-B)/(E-F)	2.55	2.67
Profitability Coefficient (PC)	D/H	3.55	4.104
Producers Subsidy Ratio (PSR)	L/E	0.68	0.717
Equivalent Producer Subsidy (EPS)	L/A	0.31	0.33

Note: The analysis was based on supplementary file tables S5 and S9.

3.2. Export parity-based PAM results (HRR = 56%)

Table 4 reports the export-parity PAM results based on a head rice recovery (HRR) of 56%, indicating that BRRI dhan50 production is both financially viable and economically efficient for export markets. At private prices, the Financial Cost-Benefit (FCB) ratio is estimated at 0.52, indicating that producers can profitably supply aromatic rice for export under prevailing market conditions.

From an efficiency perspective, the Domestic Resource Cost (DRC) is estimated at 0.91, which remains below unity and confirms a comparative advantage in export production. This indicates that the domestic resources used to produce BRRI dhan50 are valued at less than the foreign exchange earned from exports. The Social Cost-Benefit (SCB) ratio of 0.94 further supports this finding, demonstrating economic efficiency when both inputs and outputs are valued at distorted social prices. As the SCB incorporates the full opportunity cost of both tradable and non-tradable inputs, it offers a more comprehensive assessment of comparative advantage than the DRC alone.

Policy indicators highlight significant distortions in the production system. The Nominal Protection Coefficient (NPC) for output is 2.79, which exceeds unity and indicates a substantial divergence between private and social output prices. This suggests that producers receive prices above the social value of output, implying an implicit transfer from the production system to the broader economy. When policies affecting both outputs and tradable inputs are considered jointly, the Effective Protection Coefficient (EPC) of 3.55 indicates that the system benefits from overall protection, thereby increasing private value added. The Profitability Coefficient (PC) of 19.42, along with a positive net transfer of BDT 31,494, further suggests substantial transfers from the economy to BRRI dhan50 producers. In addition, the Producer Subsidy Ratio (PSR) of 1.15 confirms real support to both outputs and production factors, while the Equivalent Producer Subsidy (EPS) of 0.41 indicates considerable support. However, the structure of these interventions suggests that policy measures may favor consumers more than they directly protect producers. The export-parity PAM results indicate that BRRI dhan50 has a modest but positive comparative advantage in export markets, with profitability and competitiveness strongly shaped by existing policy measures.

3.2.1. Sensitivity analysis

Table 4 presents the results of the Policy Analysis Matrix (PAM) indicators for the export potential rice variety BRRI dhan50 under the export parity condition and a sensitivity analysis where the exchange rate increased. The results show that BRRI dhan50 remains financially profitable and economically viable despite changes in the exchange rate, although some indicators suggest a reduction in comparative advantage and social efficiency.

The financial profitability (FP) remained unchanged at BDT 33,205 under both the base and sensitivity scenarios, indicating that farmers' private profits were not directly affected by the increase in the exchange rate. Similarly, the financial cost-benefit ratio (FCB) also remained constant at 0.52, implying that production costs are substantially lower than financial returns and that the variety continues to be financially attractive for producers.

In contrast, the social profitability (SP) declined sharply from BDT 1,710 to BDT 443 when the exchange rate increased. This decrease suggests that higher exchange rates raised the economic cost of tradable inputs and reduced the net social benefit from BRRI dhan50 production. Although the SP value remained positive, the significant decline indicates that the economic gains to the national economy became relatively smaller under the sensitivity scenario.

The domestic resource cost (DRC) increased from 0.91 to 0.98 following the exchange rate increase. Since the DRC values remained slightly below one, Bangladesh still maintained a comparative advantage in exporting BRRI dhan50. However, the movement of DRC closer to unity indicates that the comparative advantage weakened considerably under higher exchange rate conditions. Similarly, the social cost-benefit ratio (SCB) increased from 0.94 to 0.983, reflecting a decline in economic efficiency, although the values below one still confirm that social benefits marginally exceeded social costs.

The transfer value increased from BDT 31,494 to BDT 32,761, indicating greater divergence between private and social profitability due to policy interventions and market distortions. The nominal protection coefficient (NPC) remained unchanged at 2.79, implying that domestic output prices were nearly three times higher than world reference prices, which reflects strong market protection for rice producers.

Moreover, the effective protection coefficient (EPC) increased from 3.55 to 3.80, indicating that domestic value-added received stronger protection under the increased exchange rate scenario. The profitability coefficient (PC) rose substantially from 19.42 to 74.95 because social profitability declined sharply while private profitability remained unchanged. This finding suggests that private profits were much higher than social profits due to policy protection and market distortions. Furthermore, the producer subsidy ratio (PSR) increased from 1.15 to 1.20, while the equivalent producer subsidy (EPS) increased from 0.41 to 0.43. These increases indicate that producers received relatively greater implicit subsidies and policy support after the exchange rate increase.

Table 4

Results of export parity-based PAM indicators of export potential rice variety considering 56% HRR.

Indicators	Equations	Main Analysis	Sensitivity Analysis
Financial Profitability (FP)	D = A-B-C	33205	33205
Financial Costs-Benefit Ratio (FCB)	C/(A-B)	0.52	0.52
Social Profitability (SP)	H = E-F-G	1710	443
Domestic Resource cost (DRC)	G/(E-F)	0.91	0.980
Social Costs-Benefit Ratio (SCB)	(F + G)/E	0.94	0.983
Transfer	L = I-J-K	31494	32761
Nominal Protection Coefficient (NPC)	A/E	2.79	2.79
Effective Protection Coefficient (EPC)	(A-B)/(E-F)	3.55	3.80
Profitability Coefficient (PC)	D/H	19.42	74.95
Producers Subsidy Ratio (PSR)	L/E	1.15	1.20
Equivalent Producer Subsidy (EPS)	L/A	0.41	0.43

Note: The analysis was based on supplementary file tables S6 and S10.

3.3. Import parity-based PAM results (HRR = 52%)

Table 5 presents a Financial Cost–Benefit (FCB) ratio at private prices of 0.51, which is below unity and indicates that BRRI dhan50 production in Jashore is financially competitive. The Domestic Resource Cost (DRC) ratio of 0.73 also confirms a comparative advantage, implying that the domestic resources used in production generate value exceeding their economic cost. The Social Cost–Benefit (SCB) ratio of 0.80 further strengthens this conclusion, demonstrating economic efficiency when evaluated at social prices. As the SCB accounts for the full opportunity cost of both tradable and non-tradable inputs, it provides a more comprehensive measure of comparative advantage than the DRC alone.

Policy indicators point to both substantial distortions and strong policy support within the system. The Nominal Protection Coefficient (NPC) of 2.38, which exceeds unity, indicates that domestic market prices for the output are significantly higher than world market prices, resulting in a positive transfer of resources to the production system. The Effective Protection Coefficient (EPC) of 2.86 indicates that the system benefits from strong overall policy protection, reflecting the combined effects of government interventions on both tradable outputs and inputs. A Profitability Coefficient (PC) of 5.12, together with a positive net transfer of BDT 27,109, indicates substantial net financial gains in favor of producers over social returns. Moreover, the Producer Subsidy Ratio (PSR) of 0.84 confirms real support to both output and production factors, while the Equivalent Producer Subsidy (EPS) of 0.35 implies that producers receive support equivalent to 35% of social revenue, with no corresponding transfer to consumers.

3.3.1. Sensitivity analysis

Table 5 presents the results of the Policy Analysis Matrix (PAM) indicators for the export potential rice variety BRRI dhan50 under import parity conditions, along with a sensitivity analysis where the exchange rate is increased. The results show that the variety remains financially profitable and economically efficient, although some indicators reflect a decline in social efficiency and comparative advantage under the higher exchange rate scenario.

The financial profitability (FP) remains constant at BDT 33,690 in both the base and sensitivity cases, indicating that farmers' private profits are not affected by the exchange rate change. Similarly, the financial cost-benefit ratio (FCB) remains stable at 0.51, confirming that production is financially efficient, as costs are significantly lower than financial returns.

In contrast, social profitability (SP) declines from BDT 6,580 to BDT 5,313 after the exchange rate increase. This reduction indicates that higher exchange rates raise the economic cost of tradable inputs, thereby reducing the net social benefit from rice production. Although SP remains positive, the decline suggests a weakening contribution to national economic welfare.

The domestic resource cost (DRC) increases from 0.73 to 0.77, indicating a slight reduction in comparative advantage. However, since the DRC remains below one, BRRI dhan50 still maintains an economic advantage in domestic production compared to imports. The increase toward unity suggests that the competitiveness of the variety is gradually weakening under the higher exchange rate condition. Similarly, the social cost-benefit ratio (SCB) increases from 0.80 to 0.84, reflecting a decline in economic efficiency, although the values below one confirms that social benefits still exceed social costs.

The transfer value increases from BDT 27,109 to BDT 28,376, indicating that producers receive higher implicit support due to policy distortions and price differences between domestic and world markets. The nominal protection coefficient (NPC) remains unchanged at 2.38, suggesting that domestic output prices are more than twice the world reference prices, reflecting a strong level of price protection.

The effective protection coefficient (EPC) increases from 2.86 to 3.02, indicating that value-added in domestic production becomes more protected under the increased exchange rate scenario. The profitability coefficient (PC) also increases from 5.12 to 6.34, showing that private profitability is substantially higher than social profitability, mainly due to policy-induced distortions. Furthermore, the producer subsidy ratio (PSR) rises from 0.84 to 0.88, while the equivalent producer subsidy (EPS) increases from 0.35 to 0.37. These increases suggest that producers receive greater implicit subsidies or protection when the exchange rate rises.

Table 5

Results of import parity-based PAM indicators of export potential rice variety considering 52% HRR.

Indicators	Equations	Main Analysis	Sensitivity Analysis
Financial Profitability (FP)	D = A-B-C	33690	33690
Financial Costs-Benefit Ratio (FCB)	C/(A-B)	0.51	0.51
Social Profitability (SP)	H = E-F-G	6580	5313
Domestic Resource cost (DRC)	G/(E-F)	0.73	0.77
Social Costs-Benefit Ratio (SCB)	(F + G)/E	0.80	0.84
Transfer	L = I-J-K	27109	28376
Nominal Protection Coefficient (NPC)	A/E	2.38	2.38
Effective Protection Coefficient (EPC)	(A-B)/(E-F)	2.86	3.02
Profitability Coefficient (PC)	D/H	5.12	6.34
Producers Subsidy Ratio (PSR)	L/E	0.84	0.88
Equivalent Producer Subsidy (EPS)	L/A	0.35	0.37

Note: The analysis was based on supplementary file tables S7 and S11.

3.4. Export parity-based PAM results (HRR = 52%)

Table 6 presents a Financial Cost–Benefit (FCB) ratio of 0.51 at private prices, which is below unity and indicates that BRRI dhan50 production in Jashore remains financially profitable for export. However, the Domestic Resource Cost (DRC) of 1.06 which exceeds one, suggests the absence of a comparative advantage in export production, as domestic resources are used less efficiently than the foreign exchange earned, leading to comparative losses. Similarly, the Social Cost-Benefit (SCB) ratio of 1.04 is greater than one, reinforcing the lack of comparative advantage when inputs and outputs are valued at distortion-free social prices. As the SCB incorporates the full opportunity costs of both tradable and non-tradable inputs, it is considered a more comprehensive and reliable indicator than the DRC alone.

Policy indicators reveal significant distortions alongside elements of policy support. The Nominal Protection Coefficient (NPC) of 3.12, which exceeds unity, suggests that the main output is overvalued at private prices, leading to a transfer of resources from the broader economy to production system. The Effective Protection Coefficient (EPC) of 4.18 indicates strong policy-induced protection affecting both tradable outputs and inputs, thereby inflating private value added. In contrast, the Profitability Coefficient (PC) of −31.78 points to net transfers from the production system to the economy (BRRI dhan50 production remains financially attractive for farmers because of strong protection and support policies, but it is not socially efficient under export parity conditions, as the economy incurs higher resource costs than the value generated at world prices.), although the reported positive net transfer of BDT 34,749 indicates that there are also simultaneous transfers benefiting producers. Furthermore, the Producer Subsidy Ratio (PSR) of 1.41 confirms substantial support to outputs and production factors, while the Equivalent Producer Subsidy (EPS) of 0.45 implies that producers receive significant net support without corresponding protection for consumers.

3.4.1. Sensitivity analysis

Table 6 presents the Policy Analysis Matrix (PAM) results for the export potential rice variety BRRI dhan50 under export parity conditions with a sensitivity analysis where the exchange rate is increased. The results indicate that while financial profitability remains stable, the variety becomes economically inefficient under social pricing after the exchange rate shock.

The financial profitability (FP) remains unchanged at BDT 33,690 in both the base and sensitivity scenarios, indicating that farmers' private profits are not affected by the increase in exchange rate. Similarly, the financial cost-benefit ratio (FCB) remains constant at 0.51, confirming that production is financially efficient from the farmers' perspective, as revenues exceed costs.

In contrast, the social profitability (SP) is negative in both cases and declines further from BDT –1,060 to BDT –2,327. This indicates that, from the viewpoint of the national economy, BRRI dhan50 production generates a net economic loss, and the loss increases when the exchange rate rises. The increase in exchange rate raises the economic cost of tradable inputs, worsening the inefficiency in resource allocation.

The domestic resource cost (DRC) increases from 1.06 to 1.15, indicating that BRRI dhan50 loses its comparative advantage under both scenarios. Since the DRC is greater than one, it implies that domestic production is less efficient (export) than importing rice. The rise in DRC further confirms a deterioration in competitiveness when the exchange rate increases. Similarly, the social cost-benefit ratio (SCB) rises from 1.04 to 1.09, reinforcing the conclusion that social costs exceed social benefits and economic efficiency declines further under the sensitivity scenario.

The transfer value increases from BDT 34,749 to BDT 36,016, indicating a widening gap between private and social values due to policy distortions and market interventions. The nominal protection coefficient (NPC) remains constant at 3.12, showing that domestic rice prices are more than three times the world price level, reflecting strong price protection for producers.

The effective protection coefficient (EPC) increases from 4.18 to 4.53, indicating greater protection of value-added in domestic production under the higher exchange rate scenario. The profitability coefficient (PC) remains negative but improves from –31.78 to –14.48, showing that although private profitability remains positive, social losses are large relative to private gains. Furthermore, the producer subsidy ratio (PSR) increases from 1.41 to 1.47, and the equivalent producer subsidy (EPS) rises from 0.45 to 0.70. These results indicate stronger implicit subsidies and policy support to producers, even though the underlying economic efficiency is weak.

Table 6

Results of export parity-based PAM indicators of export potential rice variety considering 52% HRR.

Indicators	Equations	Main Value	Sensitivity Analysis
Financial Profitability (FP)	D = A-B-C	33690	33690
Financial Costs-Benefit Ratio (FCB)	C/(A-B)	0.51	0.51
Social Profitability (SP)	H = E-F-G	-1060	-2327
Domestic Resource cost (DRC)	G/(E-F)	1.06	1.15
Social Costs-Benefit Ratio (SCB)	(F + G)/E	1.04	1.09
Transfer	L = I-J-K	34749	36016
Nominal Protection Coefficient (NPC)	A/E	3.12	3.12
Effective Protection Coefficient (EPC)	(A-B)/(E-F)	4.18	4.53
Profitability Coefficient (PC)	D/H	-31.78	-14.48
Producers Subsidy Ratio (PSR)	L/E	1.41	1.47
Equivalent Producer Subsidy (EPS)	L/A	0.45	0.70

Note: The analysis was based on supplementary file tables S8 and S12.

4. Discussion

The PAM results indicate that the competitiveness of BRRI dhan50 is highly sensitive to both market orientation (import versus export parity) and milling performance. Under import parity conditions, BRRI dhan50 exhibits a strong comparative advantage at both milling recovery levels, with DRC values of 0.65 and 0.73 at 56% and 52% HRR, respectively. In contrast, under export parity conditions, the DRC increases from 0.91 at 56% HRR to 1.06 at 52% HRR, indicating the loss of comparative advantage when milling efficiency declines. These findings suggest that competitiveness is not solely determined by production efficiency at the farm level but also by post-harvest performance and the structure of domestic and international markets.

The stronger competitiveness under import parity arises because domestic production is compared against the cost of imported rice, which includes international freight, insurance, handling, and transaction costs. These additional costs raise the import parity price and improve the relative competitiveness of domestic production. Consequently, the DRC and SCB values remain comfortably below unity under import parity, indicating that BRRI dhan50 can efficiently substitute for imports. Similar findings have been reported for rice production systems in Bangladesh and other Asian countries, where domestic rice production demonstrates stronger competitiveness in import-substitution markets than in export-oriented markets because domestic prices are generally higher than border-equivalent prices (Monke & Pearson, 1989; Yao, 1997; Gullati & Minot, 2007; Islam et al., 2016; Hossain & Deb, 2020).

The results further demonstrate the critical role of head rice recovery in determining competitiveness. A reduction in HRR from 56% to 52% causes DRC values to increase under both parity conditions and pushes export parity DRC above unity. Milling recovery directly affects the quantity of marketable rice obtained from a given volume of paddy. Higher HRR increases output without proportionally increasing production costs, thereby reducing unit costs and improving economic efficiency. Conversely, lower HRR reduces the volume of saleable whole grains while production costs remain largely unchanged, leading to higher DRC and SCB ratios. This relationship is particularly important for aromatic rice because export markets reward whole-grain quality and impose discounts on broken rice. Therefore, even a small decline in milling recovery can substantially reduce export earnings and weaken international competitiveness. Previous studies on aromatic rice value chains have similarly highlighted milling yield as a key determinant of profitability, value addition, and export performance (Bhattacharya, 2011; Tama et al., 2018; Roy et al., 2023).

The divergence between import and export competitiveness can also be explained by differences in market structure and quality requirements. Although BRRI dhan50 remains competitive under import parity at both HRR levels, export competitiveness weakens considerably and disappears at 52% HRR. Export markets require compliance with strict standards related to grain length, aroma, appearance, moisture content, and milling quality. Exporters therefore face additional costs associated with quality control, grading, packaging, certification, transportation, and international marketing. These costs reduce net export returns and lower social profitability. Furthermore, Bangladesh competes in international aromatic rice markets with established exporters such as India and Thailand, which benefit from larger production scales, more advanced milling technologies, and stronger export networks. As a result, the export parity price available to Bangladeshi producers is relatively lower, causing DRC and SCB values to increase under export-oriented scenarios (Miyata, 2011; Mohanty et al., 2017; Kannan et al., 2017; Tama et al., 2018).

The policy indicators further suggest that observed private competitiveness is strongly influenced by policy interventions and market distortions. Across all scenarios, NPC, EPC, PSR, and EPS values exceed unity, indicating significant protection and support to producers. Under import parity, NPC values ranging from 2.18 to 2.38 suggest that domestic output prices are more than double their social prices. Similarly, export parity NPC values ranging from 2.79 to 3.12 indicate a substantial divergence between domestic and world prices. These findings imply that private profitability is enhanced by policy-induced transfers, allowing producers to earn profits considerably higher than economic profits measured at social prices. Similar results have been reported in PAM studies of rice production in developing countries, where subsidies, trade restrictions, and market interventions create significant differences between private and social profitability (Monke & Pearson, 1989; Yao, 1997; Alam et al., 2011; Kassali & Jimoh, 2018).

The sensitivity analysis reveals that exchange-rate depreciation weakens comparative advantage under both import and export parity conditions. Although financial profitability remains unchanged because private prices were assumed constant, social profitability declines and both DRC and SCB increase. Under import parity, DRC rises from 0.65 to 0.68 at 56% HRR and from 0.73 to 0.77 at 52% HRR. Under export parity, DRC increases from 0.91 to 0.98 at 56% HRR and from 1.06 to 1.15 at 52% HRR. The deterioration occurs because exchange-rate depreciation raises the economic cost of tradable inputs, including different chemical fertilizers, fuel, machinery, and processing equipment. The effect is particularly severe under export parity because export competitiveness depends heavily on maintaining low production and processing costs relative to international competitors. Similar exchange-rate effects on agricultural competitiveness have been documented in rice-producing countries where imported inputs constitute a substantial share of production costs (Anderson & Martin, 2009; Anderson et al., 2013; Mohanty et al., 2017).

Overall, the findings indicate that BRRI dhan50 possesses a strong comparative advantage for import substitution but a relatively fragile comparative advantage for export promotion. The transition from export competitiveness at 56% HRR (DRC = 0.91) to export inefficiency at 52% HRR (DRC = 1.06) demonstrates that milling efficiency is a critical threshold variable for international competitiveness. Therefore, investments in modern milling technologies, improved drying and storage facilities, quality control systems, and post-harvest management practices are likely to generate larger gains in export competitiveness than farm-level productivity improvements alone. These results support previous studies emphasizing that sustaining competitiveness in aromatic rice exports requires simultaneous improvements in production efficiency, milling recovery, product quality, and market integration (Rahman et al., 2018; Tama et al., 2018; Rahman & Hasan, 2019; Roy et al., 2023).

5. Conclusion and policy recommendations

The Policy Analysis Matrix (PAM) results demonstrate that BRRI dhan50 possesses substantial potential as a competitive aromatic rice variety in Bangladesh, although its competitiveness varies considerably across market scenarios and milling recovery levels. Under import parity conditions, BRRI dhan50 consistently exhibits strong financial profitability and comparative advantage at both 56% and 52% head rice recovery (HRR) levels, as reflected by DRC and SCB values below unity. These findings indicate that domestic production can efficiently substitute for imports and contribute positively to national resource use and foreign exchange savings.

In contrast, export competitiveness is more sensitive to milling performance. At 56% HRR, BRRI dhan50 maintains a modest comparative advantage under export parity conditions (DRC = 0.91; SCB = 0.94), suggesting that exports are economically viable. However, when HRR declines to 52%, export competitiveness disappears (DRC = 1.06; SCB = 1.04), indicating that social costs exceed social benefits. This finding highlights the critical importance of milling efficiency and grain quality in determining export performance. The results further show that exchange-rate depreciation weakens social profitability and comparative advantage by increasing the economic cost of tradable inputs, although private profitability remains protected through existing policy support mechanisms.

The consistently high values of NPC, EPC, PSR, and EPS suggest that producer profitability is strongly influenced by policy interventions and market protection. While these measures enhance private returns, long-term competitiveness will depend less on policy support and more on improvements in productivity, milling efficiency, quality assurance, and export-market integration. Overall, BRRI dhan50 has stronger potential as an import-substituting aromatic rice variety than as an export commodity, although improvements in post-harvest management and milling technology could substantially strengthen its export competitiveness.

The sensitivity analysis shows that exchange-rate depreciation reduces the comparative advantage of BRRI dhan50 by increasing the economic cost of tradable inputs, resulting in higher DRC and SCB values. Although financial profitability remains unchanged, social profitability declines under both import and export parity conditions. The adverse effect is more severe for exports, where competitiveness becomes marginal at 56% HRR and disappears at 52% HRR. Therefore, sustaining competitiveness requires higher milling recovery, improved processing efficiency, and reduced dependence on imported inputs.

Based on these empirical findings, the following targeted policy interventions are recommended:

5.1. Short-term policy recommendations (1-3 years)

1. Improve milling yield and head rice recovery

Since export competitiveness is highly sensitive to HRR, immediate efforts should focus on improving milling yield through the adoption of modern milling equipment, proper paddy drying, and improved grain handling practices. Training programs should be implemented to improve harvesting, drying, storage, and post-harvest management practices. Reducing grain breakage during harvesting and processing can significantly increase HRR and improve marketable output.

2. Enhance quality control and certification

Bangladesh should strengthen quality inspection, grading, and certification systems for aromatic rice exports. Standardized quality assurance mechanisms would improve buyer confidence and help BRRI dhan50 compete in premium international markets.

3. Maintain stable input supply and market support

Policies ensuring timely access to quality seed, fertilizers, irrigation services, and extension support should continue to reduce production risks and maintain farm profitability. Temporary support measures may be necessary during periods of exchange-rate volatility and rising input costs.

4. Promote market information systems

Establishing digital platforms and export-market information systems can help farmers, traders, and exporters access real-time information on prices, quality requirements, and international demand conditions, thereby reducing market inefficiencies.

5.2. Long-term policy recommendations (4-10 years)

1. Invest in modern rice processing infrastructure

Long-term competitiveness requires substantial investment in modern milling complexes, automated grading systems, color sorting technologies, and advanced storage facilities. Improving processing efficiency would increase HRR, reduce post-harvest losses, and enhance export quality.

2. Develop an export-oriented aromatic rice value chain

Bangladesh should establish a coordinated aromatic rice value chain linking farmers, millers, exporters, research institutions, and government agencies. Contract farming and traceability systems could improve quality consistency and strengthen export market access.

3. Strengthen research and development

Public investment in rice research should prioritize the development of aromatic and premium quality rice varieties with higher milling recovery, improved grain quality, climate resilience, and export-oriented characteristics. Research on reducing post-harvest losses should also receive greater attention.

4. Improve logistics and trade facilitation

High transportation and transaction costs reduce export competitiveness. Investments in transportation infrastructure, port facilities, cold-chain logistics, and customs modernization would lower export costs and improve the competitiveness of Bangladeshi aromatic rice in global markets.

Limitation

This study is based on primary data collected from a single district (Jashore), which may not fully capture the heterogeneity of production practices, market conditions, and policy environments across Bangladesh. As a result, the findings should be interpreted with caution when generalizing to other regions. Future research should expand the scope to multiple districts and diverse agro ecological zones to provide a more comprehensive assessment of comparative advantage, export potential, and policy impacts. Incorporating broader geographic coverage would strengthen external validity and allow for more robust sensitivity analyses across varying production systems and market contexts.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alam, M. F., Begum, I. A., Buysse, J., & Van Huylenbroeck, G. (2011). Efficiency and competitiveness of rice production systems in Bangladesh. Outlook on Agriculture, 40(1), 55–63.

Anderson, K., & Martin, W. (2009). Distortions to agricultural incentives in Asia. World Bank.

Anderson, K., Ivanic, M., & Martin, W. (2013). Food price spikes, price insulation, and poverty. World Bank Policy Research Working Paper, 6532.

Anik, A. R., & Talukder, R. K. (2002). Economic and financial profitability of aromatic and fine rice production in Bangladesh. Bangladesh Journal of Agricultural Economics, 25(2), 103–113.

Antriyandarti, E. (2015). Competitiveness and cost efficiency of rice farming in Indonesia. Journal of Rural Problems, 51(2), 74–85.

Bangladesh Rice Foundation. (2005). Potential and exports of aromatic and fine rice from Bangladesh. Unpublished research report submitted to BARC, Dhaka, Bangladesh.

Bangladesh Rice Research Institute. (2025). Modern rice cultivation (25th ed., p. 128). Gazipur, Bangladesh. https://objectstorage.ap-dcc-gazipur-1.oraclecloud15.com/.

Bhattacharya, M. (2011). Spatio-temporal analysis of Indian Basmati rice trade and its comparison with Pakistan. Journal of Indian School of Political Economy, 46(2), 86–107.

Food Planning and Monitoring Unit. (2022). Database on food situation. Ministry of Food, Government of the People's Republic of Bangladesh.

Gulati, A., & Minot, N. (2007). Rice markets in South Asia: Policies and performance. International Food Policy Research Institute.

Hossain, M. A., & Deb, U. K. (2020). Competitiveness of rice production in Bangladesh: A PAM analysis. Bangladesh Journal of Agricultural Economics, 43(2), 1–20.

Islam, M. A. (2016). Comparative advantage and cost efficiency of rice-producing farms in Bangladesh: A policy analysis. Journal of Rural Problems, 52(3), 85–96.

Islam, M. A., Sumelius, J., & Bäckman, S. (2016). Do differences in technical efficiency explain the adoption of agricultural technologies? Evidence from rice production in Bangladesh. Agricultural and Resource Economics Review, 45(3), 516–540. https://doi.org/10.1017/age.2016.20

Islam, M. A., Sarkar, M. A. R., Rahman, M. C., & Rahaman, M. S. (2021a). Comparative advantage of rice production in Bangladesh: A long-term quasi-response assessment for Aman season. Fundamental and Applied Agriculture, 6(3), 279–290.

Islam, M. A., Sarkar, M. A. R., Rahman, M. C., & Rahaman, M. S. (2021b). Assessing the level of comparative advantage for Boro rice production in Bangladesh: A time series analysis. Journal of Bangladesh Agricultural University, 19(3), 361–370.

Kannan, E., Kumar, P., & others. (2017). Export competitiveness of Indian rice. In The Future Rice Strategy for India (pp. 383–411). https://doi.org/10.1016/B978-0-12-805374-4.00014-2.

Kassali, R., & Jimoh, L. O. (2018). Analysis of competitiveness of rice production using policy analysis matrix in Nigeria. Nigerian Journal of Agricultural Economics, 8(1), 1–12.

Kazal, M. M. H., Rahman, S., Alam, M. J., & Hossain, S. T. (2013). Financial and economic profitability of selected agricultural crops in Bangladesh. Food Planning and Monitoring Unit, Ministry of Food.

Minten, B., Reardon, T., & Chen, K. (2013). Quality upgrading and export competitiveness in Asian rice markets. World Development, 51, 92–108.

Mohanty, S., Wailes, E., & Chavez, E. (2017). The global rice market and competitiveness of major exporting countries. Journal of Agricultural and Applied Economics, 49(2), 234–252. https://doi.org/10.1017/aae.2017.15

Miyata, T. (2011). The Chinese market and Thai fragrant Jasmine rice. RIETI Discussion Paper Series 11-J-005.

Monke, E., & Pearson, S. (1989). The policy analysis matrix for agricultural development. Cornell University Press.

Pearson, S. R., Gotsch, C. P., & Bahri, S. (2003). Applications of the policy analysis matrix in Indonesian agriculture. Yale University Press.

Prasanna, P. A. L., & Reddy, J. R. (2025). International trade effect of geographical indications: A case study of Basmati rice exports from India. Journal of Intellectual Property Rights. https://doi.org/10.1177/09713441251389664.

Rahman, M. (2000). Rationale and mechanics of rice exports from Bangladesh (Working Paper No. 4). Food Management and Research Support Project.

Rahman, M. A., Nath, B. C., Hossen, M. A., Islam, A. K. M. S., & Paul, S. (2011). Improved processing of long grain aromatic rice. Farm Machinery Development & Dissemination Technology Project, BRRI, Gazipur, Bangladesh.

Rahman, S., & Hasan, M. (2019). Comparative advantage of rice varieties in Bangladesh. Asian Journal of Agriculture and Development, 16(1), 45–60.

Rahman, S., Wiboonpongse, A., Sriboonchitta, S., & Chaovanapoonphol, Y. (2018). Comparative advantage of rice production in South Asia. Agricultural Economics Research Review, 31(2), 215–228.

Rashid, S. R. (2009). Migration for livelihood: Social protection issues of rural Bangladeshis. In C. R. Abrar & J. Sheely (Eds.), Social protection and livelihoods: Marginalised migrant workers of India and Bangladesh (pp. 161–180). University Press Limited.

Roy, D., Rahman, M. S., & Hossain, M. I. (2023). Milling efficiency, value addition and market competitiveness of rice in Bangladesh. Bangladesh Rice Journal, 27(1), 45–58.

Shahabuddin, Q., & Dorosh, P. (2002). Comparative advantage in Bangladesh crop production (MSSD Discussion Paper No. 47). International Food Policy Research Institute.

Tama, R. A. Z., Dhar, A. R., & Begum, I. A. (2018). An economic perspective of the export potentiality of aromatic rice in Bangladesh. American Journal of Economics and Business Administration, 10, 22–30. https://doi.org/10.3844/ajebasp.2018.22.30.

Yao, S. (1997). Rice production in Thailand seen through a policy analysis matrix. Food Policy, 22(6), 547–560. https://doi.org/10.1016/S0306-9192(97)00007-4

Supplementary files

Data requirement for calculating PAM

A comprehensive data set is needed to estimate the Policy Analysis Metrics (PAM). The desired information required for constructing the PAM includes inputs, outputs, and market and social prices. For this study, we used cross-sectional data on the dry (Boro) seasons' costs and return of BRRI dhan50, and also published and unpublished secondary data from different pertinent sources. Inputs are divided into two categories: (1) traded intermediate inputs and (2) non-traded intermediate inputs.

Traded intermediate inputs

In Bangladesh, rice production typically involves the use of various fertilizers (such as urea, TSP, MoP, gypsum and ZnSO4), seeds, insecticides/pesticides, and machinery (power tiller/tractor), which are treated as traded intermediate inputs. The costs of tradable inputs are estimated using social or border parity prices. A conversion factor of 0.914 is applied for pesticides to construct the social budget (Shahabuddin and Dorosh, 2002). Although machinery is also considered a tradable input, a comprehensive dataset to estimate its social or border parity price at the farm level is not available. Therefore, market prices are used proxies for border parity prices for machinery in this study.

Seed Shadow Pricing

The shadow price of seed is calculated by applying a well-adopted formula that has been used in the relevant analysis by Antriyandarti, (2015); and Islam, (2016); Islam et. al., (2021a); Islam et. al., (2021b). The formula is as follows:

Shadow seed price = {(Actual seed cost/Actual output) × Shadow output price}

The detailed calculations of the import-parity border price of fertilizers and rice are presented in Appendix Table S1 to S4.

Non-traded intermediate inputs

Unskilled agricultural labor, manure, land rent, and interest on operating capital are considered as non-traded intermediate inputs and domestic resources because these components of the factors of production do not usually enter the international market. Irrigation equipment is regarded as a non-traded intermediate input because detailed costs for irrigation equipment are unavailable. The fees of these inputs were collected from secondary sources (such as FPMU, 2022). The specific conversion factors are used for the social valuation of these costs and prices of non-tradable inputs. We use particular conversion factors of 0.85, 0.91 and 0.79 for human labor, manure and irrigation charges respectively to construct a social budget (Shahabuddin and Dorosh, 2002). However, manure and land rental costs are used as full social costs in this study (Shahabuddin and Dorosh, 2002; BRF, 2005; Kazal et al., 2013). The opportunity cost of operating capital is calculated at 9% interest for five months of the rice production period in the Boro season. The payments for non-traded intermediate inputs and domestic resources are converted from a measurement of "per unit of the land" to "per unit of output". Methodologically, these items are valued considering their opportunity costs. In Bangladesh, factor markets are reasonably competitive, and thus, payment for non-traded intermediate inputs and domestic resources represent the opportunity costs of these resources.

Table S1

Selected FOB and CIF price and source.

Commodity	FOB/ CIF	Source
Thai Jashmin rice (aromatic) (2% broken)	FOB	Thai Rice Exporter Association, 2021; Food Outlook, 2021
Urea (Black Sea)	FOB	https://ycharts.com/indicators/black_sea_urea_bulk_spot_price
TSP (US Gulf port)	FOB	https://ycharts.com/indicators/triple_superphosphate_price
MoP (Morocco)	FOB	https://ycharts.com/indicators/potassium_chloride_muriate_of_potash_spot_price
DAP (Gulf port)	FOB	https://ycharts.com/indicators/us_diammonium_phosphate_spot_price_gulf
Gypsum (Gulf port)	FOB	https://www.statista.com/statistics/219363/wallboard-products-crude-price-in-the-us/
ZnSo4 (Gulf port)	FOB	https://www.made-in-china.com/products-search/hot-china-products/zinc_sulphate_monohydrate_price.html

Table S2

Calculation of import-parity border price of aromatic rice (BRRI dhan50), 2021-22.

Items	Base Analysis		Sensitivity Analysis	
	Engelberg (Head Rice = 52%)	Rubber huller (Head Rice = 56%)	Engelberg (Head Rice = 52%)	Rubber huller (Head Rice = 56%)
F.O.B. price at port of exit (US$/mt)	723.25	723.25	723.25	723.25
Freight charge (US$/mt)	90.07	90.07	90.07	90.07
Off. Exchange rate (1 US$ = Tk.)	**84.80**	**84.80**	**100.00**	**100.00**
A. C.I.F. price at Chattogram US$/mt	813.32	813.32	813.32	813.32
B. C.I.F. price at port of entry (Tk./mt)	68969.54	68969.54	81332.00	81332.00
C. Marketing margin from the port of entry to wholesale market (Tk./mt)	3862.68	3862.68	3862.68	3862.68
Import handling cost (Tk./mt)	1790.74	1790.74	1790.74	1790.74
Transport cost (Tk./mt)	1828.95	1828.95	1828.95	1828.95
Domestic trading cost (Tk/mt)	242.99	242.99	242.99	242.99
D. Border price at wholesale (Tk./mt) (B + C)	72832.22	72832.22	85194.68	85194.68
E. Component of marketing spread between the wholesale market to the product level (Tk./mt)	40613.54	37842.54	40613.54	37842.54
Cost from mill gate to wholesale (Tk./mt)	1588.95	1588.95	1588.95	1588.95
Milling cost (Tk./mt)	3805.60	3805.60	3805.60	3805.60
Adjustment at 52 or 56 % of milling cost (Tk/mt)	32640.00	29920.00	32640.00	29920.00
Interest cost (Tk/mt)	747.49	696.49	747.49	696.49
Cost from farm gate to mill gate (Tk/mt)	1831.50	1831.50	1831.50	1831.50
F. Border price at farmgate (Tk./mt) (D-E)	32218.68	34989.68	44581.14	47352.14
Clean rice price (Tk./kg)	32.22	34.99	44.58	47.35

Table S3

Calculation of export-parity border price of aromatic rice (BRRI dhan50), 2021-22.

Items	Base Analysis		Sensitivity Analysis	
	Engelberg (Head Rice = 52%)	Head Rice = 56%	Head Rice = 52%	Head Rice = 56%
F.O.B. price at port of exit (US$/mt)	723.25	723.25	723.25	723.25
Freight charge (US$/mt)	0	0	0	0
Off. Exchange rate (1 US$ = Tk.)	**84.8**	**84.8**	**100**	**100**
A. C.I.F. price at Chattogram US$/mt	723.25	723.25	723.25	723.25
B. C.I.F. price at port of entry (Tk./mt)	61331.60	61331.60	72325	72325
C. Marketing margin from the port of entry to wholesale market (Tk./mt)	3862.68	3862.68	3862.68	3862.68
Export handling cost (Tk./mt)	1790.74	1790.74	1790.74	1790.74
Transport cost (Tk./mt)	1828.95	1828.95	1828.95	1828.95
Trading cost (Tk/mt)	242.99	242.99	242.99	242.99
D. Border price at wholesale (Tk./mt) (B + C)	65194.28	65194.28	76187.68	76187.68
E. Component of marketing spread between the wholesale market to the product level (Tk./mt)	40613.54	37842.54	40613.54	37842.54
Cost from mill gate to wholesale (Tk./mt)	1588.95	1588.95	1588.95	1588.95
Milling cost (Tk./mt)	3805.6	3805.6	3805.60	3805.6
Adjustment at 52 of 56 % of milling cost (Tk/mt)	32640	29920	32640	29920
Interest cost (Tk/mt)	747.49	696.49	747.49	696.49
Cost from farm gate to mill gate (Tk/mt)	1831.5	1831.5	1831.50	1831.5
F. Border price at farmgate (Tk./mt) (D-E)	24580.74	27351.74	35574.14	38345.14
Clean rice price (Tk./kg)	24.58	27.35	**35.57**	**38.35**

Table S4

Border price of different chemical fertilizer (Base and sensitivity Analysis).

Items	2021-22											
	Urea	Urea (Sensitivity analysis)	TSP	TSP (Sensitivity analysis)	MoP	MoP (Sensitivity analysis)	DAP	DAP (Sensitivity analysis)	Gypsum	Gypsum (Sensitivity analysis)	ZnSo4	ZnSo4 (Sensitivity analysis)
A. F.O.B. price at port of exit (US$/mt)	361.63	361.63	527.5	527.50	202.5	202.50	574.63	574.63	75.00	75.00	575.00	575.00
B. Freight charge (US$/mt)	90.07	90.07	90.07	90.07	90.07	90.07	90.07	90.07	90.07	90.07	90.07	90.07
C. Off. Exchange rate (1 US$ = Tk.)	84.80	100.00	84.80	100.00	84.8	100.00	84.80	100.00	84.80	100.00	84.80	100.00
D. C.I.F. price at port of entry (Tk./mt)	38304	45170.00	52370	61757.00	24810	29257.00	56366	66469.54	13998	16506.54	56398	66506.54
E. Domestic handling cost (from port to wholesale) (Tk./mt)	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43	4500.43
F. Border price at wholesale (Tk./mt) (D+E)	42805	49670.43	56870	66257.43	29310	33757.43	60867	70969.97	18498	21006.97	60898	71006.97
G. Domestic handling cost (Cost from farmgate to wholesale) (Tk./mt)	895.42	895.42	1040	1040.00	1040	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00
H. Border price at farmgate (Tk./mt) (F+G)	43700	50565.85	57910	67297.43	30350	34797.43	61907	72009.97	19538	22046.97	61938	72046.97
I. Border price at farmgate (Tk./kg)	43.70	50.57	57.91	67.30	30.35	34.80	61.91	72.01	19.54	22.05	61.94	72.05

Table S5

Results of export parity-based PAM indicators of export potential rice variety considering 52% HRR.

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76307	7796	35306	33205
Social	34989	8078	17562	9349
Divergences	41318	-281	17744	23855

Source: Field survey, 2021-22
Note: Import parity: Head rice recovery ratio considered 56%

Table S6

Results of PAM of export potential rice variety (BRRI dhan50).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76307	7796	35306	33205
Social	27350	8078	17562	1710
Divergences	48957	-281	17744	31494

Source: Field survey, 2021-22
Note: Export parity: Head rice recovery ratio considered 56%

Table S7

Results of PAM of export potential rice variety (BRRI dhan50).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76792	7796	35306	33690
Social	32220	8078	17562	6580
Divergences	44572	-281	17744	27109

Source: Field survey, 2021-22
Note: Import parity: Head rice recovery ratio considered 52%

Table S8

Results of PAM of export potential rice variety (BRRI dhan50).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76792	7796	35306	33690
Social	24580	8078	17562	-1060
Divergences	52212	-281	17744	34749

Source: Field survey, 2021-22;
Note: Export parity: Head rice recovery ratio considered 52%

Table S9

Results of PAM of export potential rice variety (BRRI dhan50) (Sensitivity analysis).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76307	7796	35306	33205
Social	34989	9345	17562	8082
Divergences	41318	-1548	17744	25122

Source: Field survey, 2021-22
Note: Import parity: Head rice recovery ratio considered 56%

Table S10

Results of PAM of export potential rice variety (BRRI dhan50) (Sensitivity analysis).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76307	7796	35306	33205
Social	27350	9345	17562	443
Divergences	48957	-1548	17744	32761

Source: Field survey, 2021-22
Note: Export parity: Head rice recovery ratio considered 56%

Table S11

Results of PAM of export potential rice variety (BRRI dhan50) (Sensitivity analysis).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76792	7796	35306	33690
Social	32220	9345	17562	5313
Divergences	44572	-1548	17744	28376

Source: Field survey, 2021-22
Note: Import parity: Head rice recovery ratio considered 52%

Table S12

Results of PAM of export potential rice variety (BRRI dhan50) (Sensitivity analysis).

Items	Revenue	Tradable inputs	Non-tradable inputs	Profit
Private	76792	7796	35306	33690
Social	24580	9345	17562	-2327
Divergences	52212	-1548	17744	36016

Source: Field survey, 2021-22;
Note: Export parity: Head rice recovery ratio considered 52%

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