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Abstract

Pre-monsoon *Aus* rice has the potential to strengthen Bangladesh's rice-based farming systems, particularly in drought-prone regions where water scarcity, climate variability, and rising production costs threaten the sustainability of irrigated *Boro* rice. Growing improved *Aus* rice varieties using dry direct seeding could improve water and input-use efficiency, reduce greenhouse gas emissions, and increase farm profitability. However, evidence on the agronomic performance, economic viability, and environmental impacts of recently released *Aus* rice varieties under dry direct-seeded conditions remains limited. Therefore, this study evaluated the agronomic, economic, and environmental performance of five *Aus* rice genotypes under dry direct-seeded conditions across two major rice-growing regions of Bangladesh (Rangpur and Rajshahi) during the 2023–2025 *Aus* seasons, encompassing six environments (E1–E6). Field experiments were conducted on farmers' fields using head-to-head adaptive trials arranged in a randomized complete block design with four replications at each site. The evaluated varieties were BRRI dhan75 (benchmark), BRRI dhan82, BRRI dhan85, BRRI dhan98, and BRRI dhan48 (farmers' check). Key performance indicators included grain yield, canopy cover, crop duration, yield advantage, gross return, benefit-cost ratio (BCR), and greenhouse gas intensity (GHGI). Among the tested varieties, BRRI dhan98 consistently produced superior yields and generated higher gross returns than the other entries. In Rajshahi, BRRI dhan98 achieved a 20% yield advantage over the farmers' check (BRRI dhan48) and a 10% advantage over the benchmark variety (BRRI dhan75). In contrast, BRRI dhan75 showed better performance in Rangpur. Higher benefit-cost ratios were recorded for BRRI dhan98 (2.3) and BRRI dhan75 (2.6), exceeding that of the farmers' check,

BRRI dhan48 (2.0). Environmental assessment showed relatively similar total CO₂ emissions across varieties, although GHGI varied moderately, with the lowest values observed for BRRI dhan98 and the highest for BRRI dhan48 and BRRI dhan82. Overall, the results suggest that dry direct-seeded rice, combined with well-adapted varieties such as BRRI dhan98 and BRRI dhan75, can improve productivity and profitability without increasing greenhouse gas intensity. These results highlight the potential of targeted varietal selection and site-specific management to optimize both economic returns and climate resilience in Bangladesh's evolving rice systems.

Keywords: AMMI biplot; benefit-cost ratio; direct-seeded rice; greenhouse gas intensity; gross return advantage; yield advantage

1. Introduction

Rice supports the diets of over four billion individuals worldwide. i.e., more than half the world's population (FAO, 2025). In Asia, where around 90% of the world's rice is both produced and consumed, rice supplies more than half of the daily caloric intake for a majority of the population, signifying its central role in food security (Bandumula, 2018; Mohidem et al., 2022; Asian Development Bank, 2010).

In Bangladesh, rice is the staple food crop and comprises around 92% of the total food grain production. Farmers cultivate rice in three seasons, namely *Aus*, long-duration rainfed *Aman*, and irrigated *Boro*. The largest segment of rice production is *Boro*, and the smallest segment is *Aus*. In 1971, around three million hectares of land were under *Aus* cultivation, and the average volume of production harvested was around 0.78 tons/ha. The rice cropping system experienced large-scale changes in 2022, when land area used for rice production declined by around 1.2 million hectares, but average production jumped to 2.85 tons/ha (BRRI, 2023), showcasing the impact of new varieties and technologies enabling sustainable intensification in farming systems in the country. The production of the *Aus* season continues to play a significant role in feeding overpopulated geographies in Bangladesh.

Labour constraints and climate change are major issues in rice-growing systems. Availability of agricultural labourers is decreasing, and labour wages are increasing. The agricultural labour shortage, along with rising water scarcity, has resulted in increased cost of production of rice and impacted food security (Ahmed et al., 2016). Looming water crisis, water-intensive nature of rice cultivation, and escalating labor costs drive the search for alternative management methods to increase water productivity in rice cultivation (Ahmed et al., 2025).

A major issue in traditional rice-growing systems is the reliance on flooded water systems. Pumping groundwater for irrigation in Bangladesh is energy-intensive and predominantly relies on diesel, contributing significantly to greenhouse gas (GHG) emissions. Irrigation-related GHG

emissions amount to approximately 2.27 million tons (Mt) CO₂e annually, comprising 4% of the agricultural sector's emissions. Groundwater pumps are the largest contributors to GHG emissions at 2.04 Mt CO₂e annually, and surface water pumps account for only 0.23 Mt CO₂e (Maniruzzaman et al., 2025). Rajshahi, Rangpur, and Mymensingh regions in Bangladesh experience high emissions due to intensive groundwater use. Current irrigation methods - deep and shallow tubewells and low lift pumps- cover significant cultivable areas and are responsible for 49.1%, 40.6%, and 10.3% of GHG emissions, respectively, from irrigated rice (Maniruzzaman et al., 2025). Therefore, *Aus* and *Aman* rice can play a significant role in reducing dependence on *Boro*-season rice, helping to restore water availability and mitigate GHG emissions.

Direct-seeded rice (DSR) has received much attention in the last decade because of its low-input demand. DSR is a climate-smart crop establishment method where seeds are sown directly into the field without transplanting seedlings from a nursery, thereby avoiding continuous flooding (Ahmed et al., 2021). It can be either dry or wet seeding, depending on field conditions. Dry or wet seeding rice could serve as an alternative to the traditional puddle-transplanted rice (PTR), potentially reducing CH₄ emissions and water use in rice cultivation (Chaudhary et al., 2022). PTR relies on continuous flooding that creates anaerobic conditions, promoting methanogenic bacteria responsible for CH₄ emissions (Islam et al., 2020; Gaihre et al., 2025). Conversely, DSR is often cultivated under non-flooded or intermittently irrigated conditions that foster aerobic environments (Bari and Ahmed, 2018). These aerobic conditions inhibit methanogenic bacteria and support methanotrophs, which convert CH₄ into CO₂ before it is released into the atmosphere (Liu, 2022; Ahmed et al., 2025). However, according to Gaihre et al. (2015) and Islam et al. (2018), aerobic conditions may enhance N₂O emission due to nitrification, with a global warming potential (GWP). Also, this method may increase weed infestation. Additionally, the impact of DSR on rice yields remains inconsistent, necessitating long-term studies across different agro-ecological zones of Bangladesh to determine its true effect on rice production (Ahmed et al., 2025).

Traditionally, *Aus* rice in Bangladesh was established by broadcasting local varieties, resulting in low yields, poor input-use efficiency, and limited economic returns. Advances in mechanized seeding, improved *Aus* cultivars, and refined crop management practices have increased the feasibility of dry direct-seeded *Aus* rice. In suitable rainfed environments, this production system could replace part of the input-intensive *Boro* rice area by reducing irrigation requirements, labor demand, and production costs while improving resource-use efficiency and enhancing the resilience of rice-based farming systems.

Head-to-head adaptive trials (HHATs) are an advanced and widespread method and a relatively simple approach for evaluating and comparing the performance of alternative technologies under farmers' field conditions with participatory approaches (Akter et al., 2025). The participatory approach increases the acceptance and adoption of new technologies (e.g., varieties) by

encouraging greater involvement and knowledge sharing as well as building farmers' confidence in the efficacy of the new technologies (Debsharma et al., 2024).

Although BRRI has released rice varieties for dry direct seeding, such as BRRI dhan65 and BRRI dhan83, their adoption during the *Aus* season has remained limited because of variable yield performance, and inconsistent crop establishment. In contrast, several improved *Aus* rice varieties were developed specifically for the *Aus* season under transplanted conditions, but their suitability for dry direct seeding has received little attention. Most previous studies have focused primarily on grain yield, with limited information available on yield stability across environments, economic performance, and GHG footprint under DSR conditions. Therefore, this study evaluated the agronomic performance, yield stability, economic viability, and GHG emissions of selected improved *Aus* rice varieties under DSR conditions across multiple years and locations in northern Bangladesh. The results provide evidence to identify varieties that combine stable productivity, profitability, and lower environmental impacts for dry DSR *Aus* rice systems.

2. Materials and Methods

2.1 Study Area

This study was conducted in the northern region of Bangladesh, specifically in two districts: Godagari in the Rajshahi district of Rajshahi division and Rangpur Sadar in the Rangpur district of Rangpur division. The experimental on-farm trials (OFTs) were implemented in the farmers' fields using the HHAT method following the triadic comparison of technologies (TRICOT) model (van Etten et al., 2019). In this method, different agricultural technologies, especially improved crop varieties and germplasms, are easily compared and evaluated on the basis of certain characteristics. The main purpose of varietal HHATs is to compare the yield and performance of new experimental varieties with farmers' check and popular benchmark varieties in the farmers' fields under farmers' management conditions. As a result, the performance of new varieties in the DSR method of cultivation can be studied and findings witnessed by the farmer, including identification of key traits, varietal performance, and the impact of new varieties (Akter et al., 2025). The experiments were carried out from the last week of May to the first week of August, i.e., the *Aus* (pre-monsoon) season, over two consecutive years (2023, 2014 and 2025) (Rad et al., 2013). These two geographic locations represent distinct agro-ecological zones (AEZs) of Bangladesh and capture variations in land type, temperature, rainfall, and overall agro-climatic conditions.

Rangpur: The study site in this district was Maheshpur village, located in Rangpur Sadar Upazila (Lat – 25°47'37.04'' N and Lon – 89°6'29.94'' E). This area lies within AEZ 3 of the 30 AEZs (BARC, 2012) delineated by the Department of Agricultural Extension (DAE). The land type in the region is also high to medium highland, dominated by the Tista Meander Floodplain (TMF)

(**Table 1**). The average annual rainfall in 2024 was approximately 142 mm, and the average minimum and maximum temperatures were 24.25°C and 30.66°C, respectively (**Figure 1**).

Rajshahi: The study site in this district was Bijohnagar village, located in Godagari Upazila (Lat – 24°24'16.2'' N and Lon – 88°26'12.8'' E). This area falls within AEZ 11 of the 30 AEZs (**BARC, 2012**) defined by the DAE. The land type in this region is predominantly high to medium highland, characterized by the High Ganges River Floodplain (HGRF) (**Table 1**). The average annual rainfall in 2024 was approximately 103 mm, while the average minimum and maximum temperatures were 26.64°C and 31.9°C, respectively (**Figure 1**).

	Rangpur	Rajshahi
Environmental Code	E1 (ENV1, ENV2, and ENV3 - representing the years 2023,2024, and 2025, respectively)	E2 (ENV4, ENV5, and ENV6 - representing the years 2023,2024, and 2025, respectively)
AEZs	Tista Meander Floodplain	High Ganges River Floodplain
Soil Type	Olive brown, rapidly permeable, loamy soils on the upper land and grey or dark grey, slowly permeable, heavy silt or clay loam on lower land	Olive brown, silt & clay loams on the upper floodplain and dark grey, mottled brown, clay soils on lower floodplains.

Table 1. Site characteristics of Rangpur and Rajshahi
Source: **Agro-Ecological Zones Maps, (n.d.)**

2.2 Climatic Conditions of the Study Area

In both areas, rainfall is highest during the monsoon season (June, July, and August), when rainfall increases significantly. Both E1 and E2 received the highest rainfall in July, indicating a full monsoon season, and it continued to be high in August (**Figure 1**). Under normal conditions, with the onset of the monsoon in June, rainfall increases rapidly, which is crucial for the early growth stage of *Aus* rice. Rainfall then slowly begins to decrease in September, which is helpful in harvesting *Aus* rice and preparing for the next season.

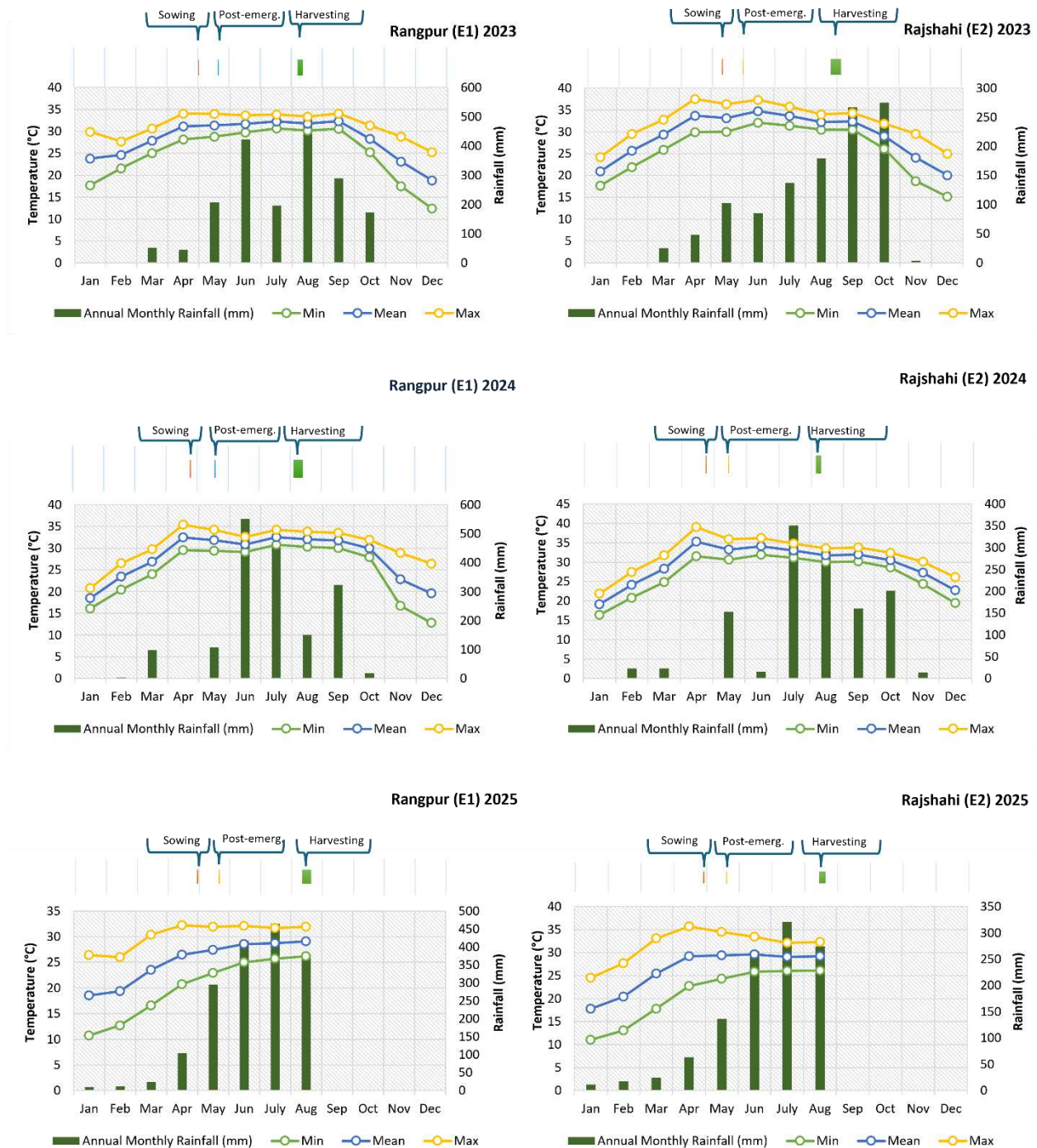


Figure 1. Seasonal weather patterns of E1 and E2 during the experimental years 2023-25 (Bangladesh Meteorological Department, 2026). The figure illustrates the alignment of the *Aus* rice season with regional rainfall and temperature trends in both districts. The *Aus* crop is typically planted in the last week of April, coinciding with the onset of the rainy season, and harvested between the last week of August and the first week of September, allowing timely establishment of the subsequent early *Boro* crop.

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174 **2.3. Selected Rice Varieties and Their Descriptions**

175 The selected rice varieties used in this experiment were drawn from the DELS-R (direct seeded,
 176 early duration, long slender, soft grain rice for upland shallow areas) market segment as nominated
 177 by National Agricultural Research and Education System (NARES) scientists. The varieties
 178 included BRRI dhan98, BRRI dhan85, BRRI dhan82, BRRI dhan75, and BRRI dhan48. Among
 179 these, BRRI dhan75 served as the benchmark variety, and BRRI dhan48 was designated as the
 180 farmers' check variety, while the remaining varieties were used as test entries (**Table 2**). The
 181 HHAT variety selection strategy involves the systematic inclusion of both newly developed and
 182 established varieties through processes such as market segmentation, product nomination, and the
 183 identification of benchmark and farmers' check varieties (Nayak et al., 2022).

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#	Genotype name	Varietal Code	Genotype Code	Variety Description	Total Seed quantity used for the experiment	Number of trial plots	Total area for the experiment
1	BRRI dhan48	Farmers' Check	G ₁	Pedigree: BR1543-9-2-1/IR13249-49-3-2-2, Grain type: Medium bold, Potential yield: 5.5 t ha ⁻¹ , Duration: 110 days, Rainfed	72 kg	72	9.63 ha
2	BRRI dhan75	Benchmark	G ₂	Pedigree: Yuefengzhan/E-Zhong 5, Grain type: Medium slender, Potential yield: 4.5-5.5 t ha ⁻¹ , Duration: 110-115 days, Rainfed	72 kg	72	
3	BRRI dhan82	Test Variety	G ₃	Pedigree: Pure line selection of NERICA10, Grain type: Medium bold, Potential yield: 4.5-5.5 t ha ⁻¹ , Duration: 100-105 days, Rainfed	72 kg	72	
4	BRRI dhan85	Test Variety	G ₄	Pedigree: BR4828-54-1-4-9/IR50//BR4828-54-1-4-9/LUHONG ZAO1, Grain type: Medium long slender, Potential yield: 4.5-5.5 t ha ⁻¹ , Duration: 108-110 days, Rainfed	72 kg	72	
5	BRRI dhan98	Test Variety	G ₅	Pedigree: MLT-145-2/HR17512-11-2-3-1-4-2-3, Grain type: Long slender, Potential yield: 5.09-5.87 t ha ⁻¹ , Duration: 112 days, Rainfed	72 kg	72	

Table 2. Rice genotypes used in the HHAT experiments

2.4. Experimental Design

HHATs were conducted in both locations during the *Aus* seasons of 2023, 2024, and 2025, using DSR as the crop establishment method. The experimental plots were laid out following a randomized complete block design (RCBD) to ensure the best possible comparison between varieties. The positions of the varieties within each block were randomized before planting. Three categories of treatments were included in the layout: test varieties, farmers' check variety, and benchmark variety. In this experimental design, RCBD ensures that each variety has an equal number of replications, improving the reliability and accuracy of comparative analyses. The RCBD approach ensured optimal data collection, evaluation, and comparison of crop performance and agronomic traits under uniform field conditions (Paswan et al., 2014).

2.5 Crop Management

Seeds of each variety were dry direct-seeded at a rate of 40 kg ha⁻¹ using a power tiller-operated seeder (PTOS). Before sowing, all fertilizers except urea were applied according to BRRI recommendations, whereas urea was applied in three equal splits. A pre-emergence herbicide, pendimethalin (1.0 kg a.i. ha⁻¹), was applied within two days after sowing, followed by the post-emergence herbicide bispyribac-sodium (25 g a.i. ha⁻¹) at 20-25 days after sowing. One or two hand weedings were carried out as needed. Supplemental irrigation was applied only when hairline cracks appeared in the soil. Pests and diseases were managed following standard recommended practices.

2.6. Data Collection and Statistical Analysis

Rice Grain Yield and Crop Duration

Grain yield (t ha⁻¹) was recorded at harvest by collecting samples (3 m by 2 m) from the central rows of each plot to minimize border effects. The harvested grains were cleaned and sun-dried to approximately 14% moisture content and then weighed and converted to yield per hectare.

Crop duration (days) was calculated as the number of days from sowing to 85% physiological maturity, defined as the stage when the majority of panicles in each plot had turned golden yellow.

Canopy Coverage

Canopy coverage (%) was measured at the maximum vegetative growth stage using a digital canopy analyzer. Observations were recorded from the central portion of each plot to minimize border effects and ensure accurate representation of plant canopy development.

Economic analysis

All variable costs, including land preparation, seed, fertilizers, herbicides, insecticides, fungicides, irrigation, and labor for field operations (land preparation, seeding/transplanting, irrigation, fertilizer and pesticide application, and weeding), were included in the economic analysis. Labor use was recorded as person-days ha⁻¹, with the time required for each operation measured in hours and converted to person-days assuming 8 h = 1 person-day, following the Bangladesh Labour Act. Labor costs were estimated using the prevailing local wage rate. Irrigation costs were calculated based on the local hourly irrigation charge plus the associated labor cost. Gross income was estimated using the farmgate price of grain and the local market price of straw, calculated by multiplying grain yield by the grain price and adding the value of straw.

Descriptive statistics were computed for each genotype and trait, including the mean ($\bar{x}$), standard deviation (SD), minimum, maximum, and coefficient of variation (CV, %).

Best Linear Unbiased Estimators (BLUEs): BLUEs are used when genotypes are treated as fixed effects, meaning the focus is on estimating the specific performance of the genotypes included in the trial (**Henderson, 1975**). The BLUEs represent the estimated mean yield for each genotype, adjusted for environmental effects and other factors. Best Linear Unbiased Predictors (BLUPs): BLUPs are used when genotypes are treated as random effects, meaning the goal is to predict the genetic potential of these genotypes for future use or across a wider range of environments (**Piepho et al., 2008**). BLUPs account for the genetic relationships between genotypes and adjust for environmental variation, providing a more accurate estimate of a genotype's true breeding value. Predicted Mean Grain Yield: The predicted mean grain yield for each genotype is a crucial output of the mixed-model analysis. It combines the overall population mean with the genotype's specific BLUP value. This predicted value provides a more reliable estimate of a genotype's performance than a simple arithmetic mean, as it is "shrunk" towards the overall mean to account for the reliability of the genotype's data.

The predicted mean (**Piepho et al., 2008**) is calculated as

Predicted Mean = Overall Mean + BLUP value

Data Visualization and Plotting: The comparison of BLUEs and BLUPs was visualized using a scatter plot. This plot was generated to graphically represent the relationship between the fixed-effect estimates (BLUEs) and the random-effect predictions (BLUPs) for each genotype.

Generating this plot involved the following steps:

1. Axis Assignment: The calculated BLUE values for each genotype were assigned to the horizontal (x) axis, representing the estimated genotypic performance. The calculated BLUP

values were assigned to the vertical (y) axis, representing the predicted breeding value (genetic potential) of each genotype.

2. Plot Point Mapping: Each test variety was plotted as a discrete point on the graph. The coordinates of each point were determined by its corresponding BLUE and BLUP pair.

Analysis of Variance (ANOVA): ANOVA was conducted to partition the total variation in the data into components attributable to the main effects of environment (ENV) and genotype (GEN), and their interaction (GEN x ENV) (Gomez & Gomez, 1984; Yan & Kang, 2002).

Cluster Analysis: The dissimilarity matrix was then subjected to hierarchical cluster analysis using Ward's minimum variance method (Ward, J. H. 1963). This algorithm works by iteratively merging the pair of clusters that results in the smallest increase in the total within-cluster sum of squares. This process continues until all genotypes are grouped into a single cluster.

All statistical analyses were performed using R software (version 4.5.1) with the appropriate packages.

For comparative performance analysis, data on grain yield, selling price, total returns, and production cost were used to calculate yield advantage (YA), gross return advantage (GRA), and benefit-cost ratio (BCR). Greenhouse gas parameters, including total greenhouse gas intensity (GHGI), were also included in the analysis. These indicators collectively quantified the economic and environmental efficiency of each genotype under DSR management.

Yield advantage (%) of the genotypes through the DSR trial experiment is calculated as

$$YA (\%) = \frac{\overline{GY}_{candidate} - \overline{GY}_{reference}}{\overline{GY}_{reference}} \times 100$$

Where candidate is the test variety (G₃, G₄, G₅); reference is the farmer's check (G₁) or benchmark (G₂)

$\overline{GY}$ is the mean grain yield of the genotype

Gross return advantage (%) of the genotypes is calculated as

$$GRA (\%) = \frac{(Y_{candidate} \times SP_{candidate}) - (Y_{reference} \times SP_{reference})}{Y_{reference} \times SP_{reference}} \times 100$$

Where Y is the yield.

SP is the selling price.

Candidate and reference are as explained above.

The benefit-cost ratio is used to assess economic performance, where higher BCR values indicate greater profitability and improved economic feasibility of the evaluated cultivars under direct-seeded rice conditions. The BCR for a genotype was then derived from the ratio of total returns from its cultivation to total costs of production as

$$BCR = \frac{\text{Total Return (TR)}}{\text{Total Cost of Cultivation (TC)}}$$

Where TR (Tk ha⁻¹) is computed by multiplying yield by the corresponding selling price.

TC (Tk ha⁻¹) is the sum of the expenses for land preparation, seed, fertilizers, irrigation, labor, weed management, harvesting, and other management practices.

Total Greenhouse Gas Intensity was estimated using the IRRI-developed source-selective and emission-adjusted GHG calculator (SECTOR). SECTOR is a GHG calculator based on the IPCC Tier 2 approach for rice and other crops. The tool is an MS Excel file and requires data on crop area, yield, and management. GHGI was computed as the emission per unit of yield, expressed as kg CO₂e per kg of paddy, to allow direct comparison among genotypes and sites (**SECTOR Tool, n.d.**).

3. Results

Grain yield differed significantly among genotypes and locations (**Supplementary Table 1**). In Rangpur (E1), BRRI dhan75 and BRRI dhan98 produced the highest yields, whereas BRRI dhan98 was superior in Rajshahi (E2). Across environments, BRRI dhan98 recorded the highest overall mean yield, while BRRI dhan85 showed the greatest yield stability. BLUE, BLUP, and predicted mean yield estimates confirmed these trends (**Table 3**), with positive BLUP values for BRRI dhan98 indicating broad adaptation and negative values for BRRI dhan48 and BRRI dhan82 indicating below-average performance. Canopy cover and harvest duration also varied among genotypes. BRRI dhan48 had the greatest canopy cover, whereas BRRI dhan82 had the lowest. BRRI dhan48 and BRRI dhan75 matured later than BRRI dhan82, BRRI dhan85, and BRRI dhan98. Environment, genotype, and GEN x ENV interaction significantly affected grain yield, canopy cover, and harvest duration (**Supplementary Table 2**).

#	ID	Location	Genotype	BLUE	BLUP	Predicted Mean Grain Yield
1	BRRI dhan48 (farmers' check)	E1	G1	3.92	-0.46	3.45
		E2		3.73	-0.23	3.50
		Combined (E1 & E2)		3.82	-0.35	3.48
2	BRRI dhan75	E1	G2	4.74	0.34	5.08

	(benchmark)	E2		3.91	-0.05	3.86
		Combined (E1 & E2)		4.33	0.15	4.47
3	BRRI dhan82 (test variety)	E1	G3	4.11	-0.28	3.83
		E2		3.56	-0.40	3.16
		Combined (E1 & E2)		3.83	-0.34	3.50
4	BRRI dhan85 (test variety)	E1	G4	4.48	0.09	4.58
		E2		4.05	0.09	4.14
		Combined (E1 & E2)		4.27	0.09	4.36
5	BRRI dhan98 (test variety)	E1	G5	4.70	0.30	5.01
		E2		4.56	0.59	5.16
		Combined (E1 & E2)		4.63	0.45	5.08

Table 3. Estimated BLUEs, BLUPs, and predicted mean grain yield of rice genotypes at E1 and E2

Canopy Coverage

Figure 2 illustrates the AMMI1 biplot for canopy coverage across locations and years. BRRI dhan75 showed the greatest stability for canopy cover in both locations. Across environments, BRRI dhan48 and BRRI dhan75 combined relatively high canopy cover with greater stability, whereas BRRI dhan85 and BRRI dhan98 displayed stronger environmental responses. BRRI dhan82 consistently had the lowest canopy coverage.

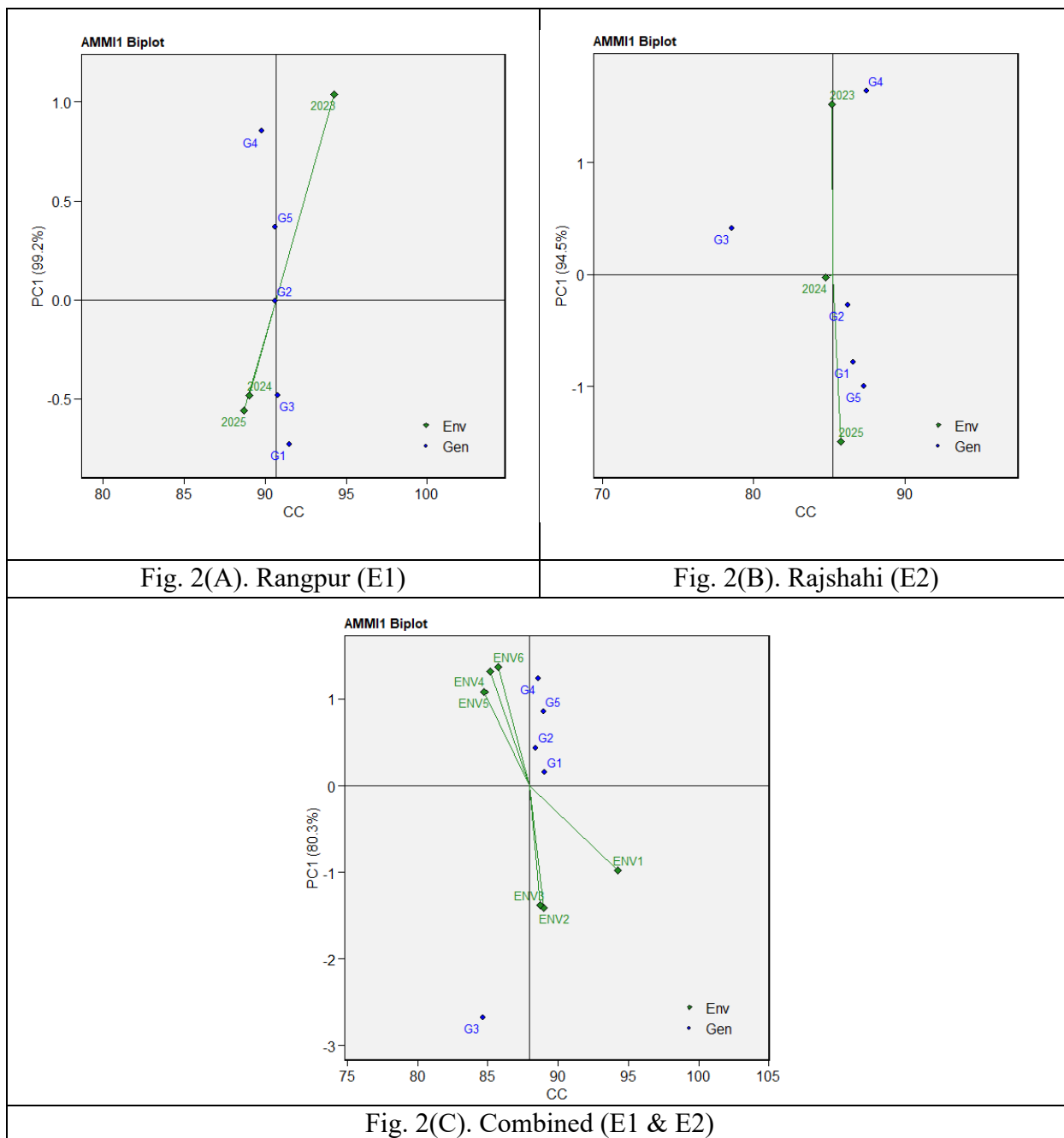


Figure 2. AMMI1 biplot for canopy coverage illustrating genotype-by-environment interaction effects across environments E1, E2, and Combined (E1 & E2) over the years. E1= Rangpur, E2= Rajshahi; AMMI = Additive Main Effects and Multiplicative Interaction; PC=Principal Component

Crop Duration

The AMMI1 biplot in **Figure 3** illustrates the GEI for crop duration across years. Crop duration varied among genotypes and environments. BRRI dhan48 and BRRI dhan75 were relatively late

maturing, whereas BRRI dhan82, BRRI dhan85, and BRRI dhan98 matured earlier. Across environments, BRRI dhan82 exhibited the greatest stability for crop duration, while Rangpur showed greater environmental variation than Rajshahi.

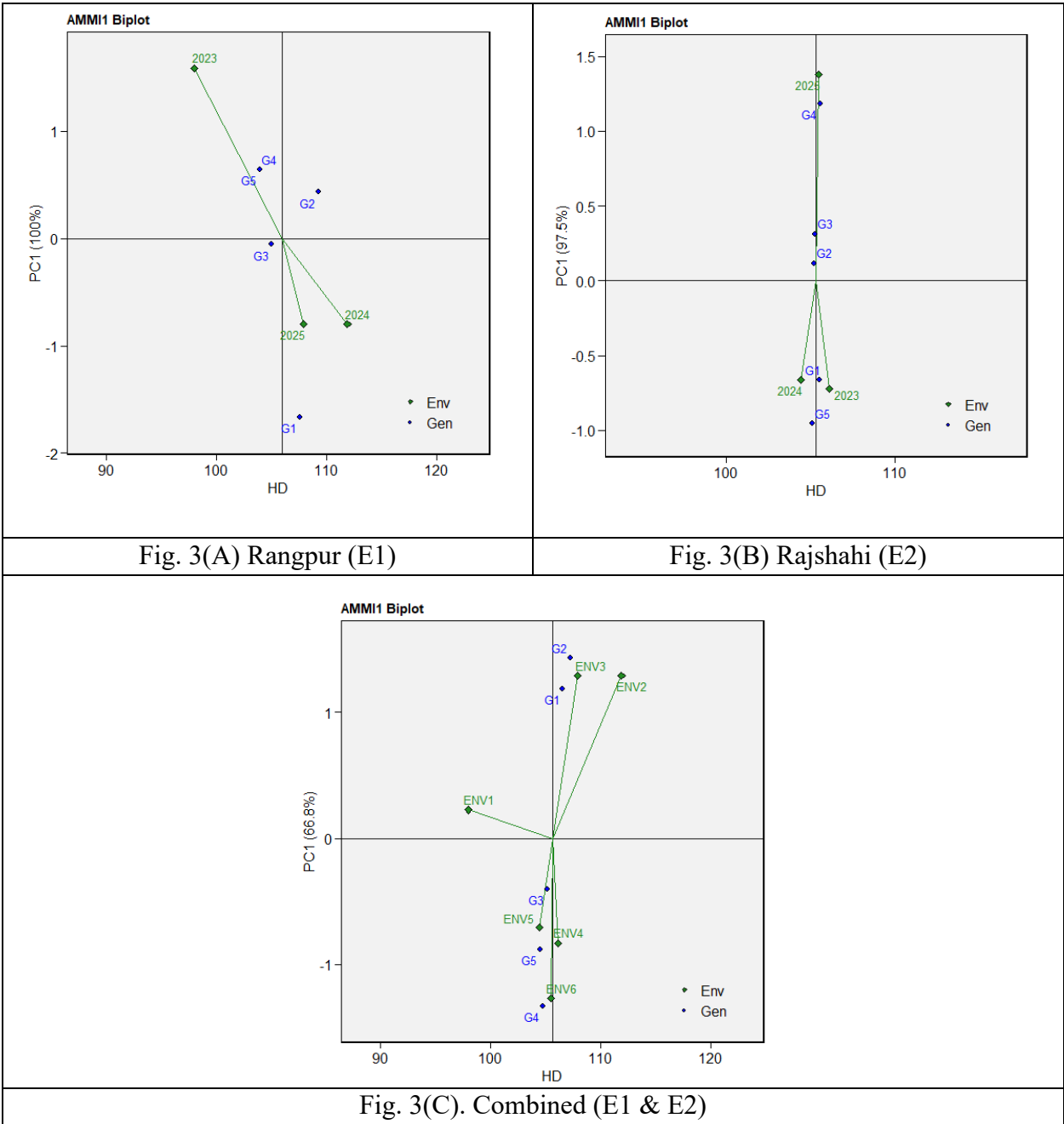


Figure 3. AMMI1 biplot for crop duration illustrating genotype-by-environment interaction effects across environments E1, E2, and Combined (E1 & E2) over the years. E1= Rangpur, E2= Rajshahi; AMMI = Additive Main Effects and Multiplicative Interaction; PC=Principal Component

Grain Yield

Figure 4 illustrates the AMMI biplot for GEI for grain yield across locations and years. AMMI analysis showed that BRRI dhan75 combined high yield with good stability in Rangpur, whereas BRRI dhan98 was the highest-yielding genotype in Rajshahi. Across environments, BRRI dhan98 achieved the highest mean yield, while BRRI dhan85 showed comparatively greater stability. BRRI dhan48 and BRRI dhan82 consistently ranked among the lowest-yielding genotypes.

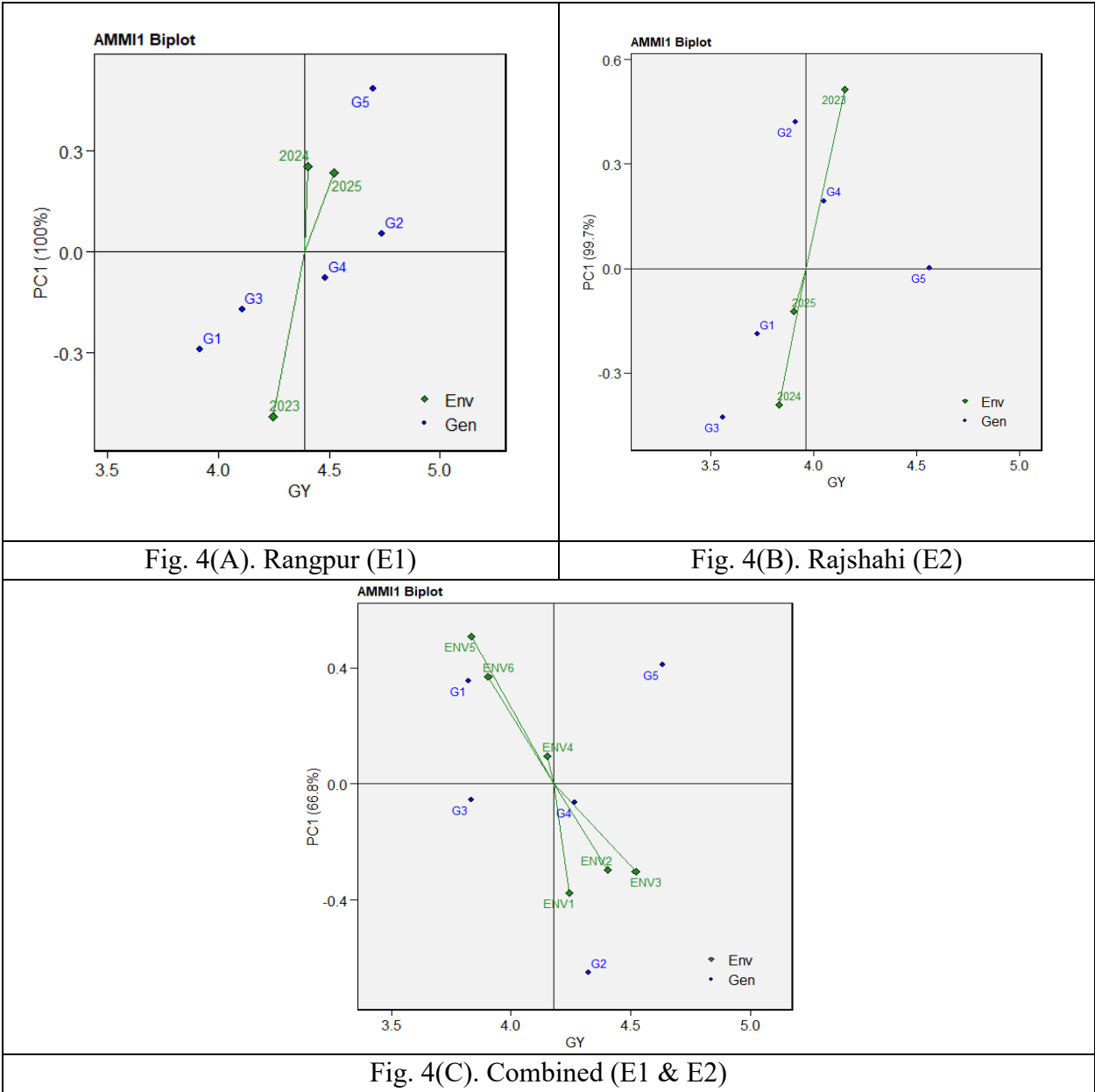
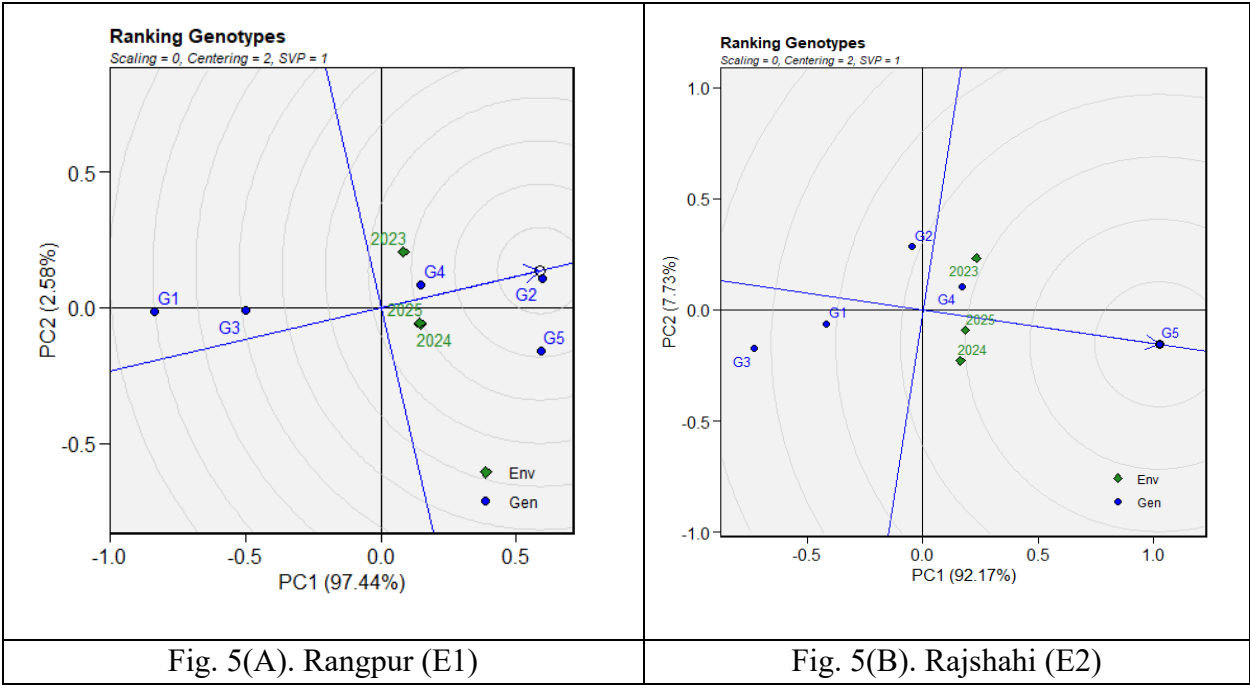


Figure 4. AMMI1 biplot for grain yield illustrating genotype-by-environment interaction effects across environments E1, E2, and Combined (E1 & E2) over the years. E1= Rangpur, E2= Rajshahi; AMMI = Additive Main Effects and Multiplicative Interaction; PC=Principal Component

3.1 Performance Ranking

The AMMI biplot in **Figure 5** ranks genotypes based on the average performance and stability. Genotype ranking confirmed BRRI dhan75 as the best performer in Rangpur and BRRI dhan98 in Rajshahi. Across all environments, BRRI dhan98 ranked highest overall, whereas BRRI dhan48 consistently ranked lowest.



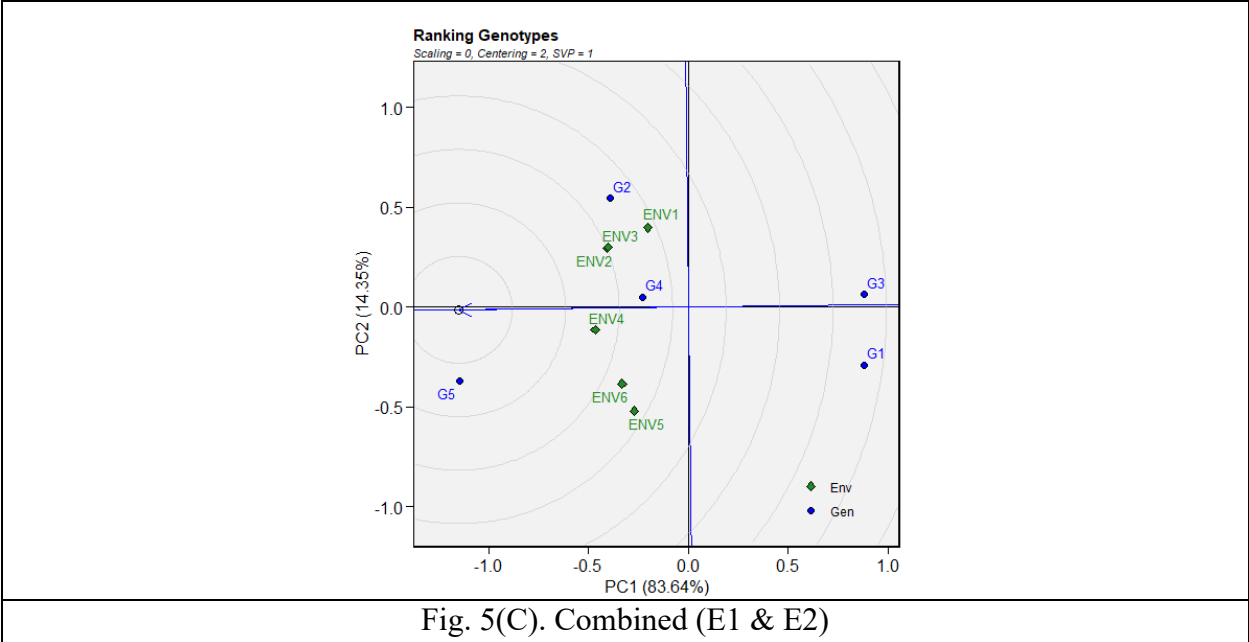


Fig. 5(C). Combined (E1 & E2)

Figure 5. AMMI biplot for ranking genotypes based on their yield and stability in different years across E1, E2, and Combined (E1 & E2). E1= Rangpur, E2= Rajshahi; AMMI = Additive Main Effects and Multiplicative Interaction; PC=Principal Component

In the scatter plot (**Figure 6**) BLUEs and BLUPs are strongly associated across environments, indicating reliable prediction of genetic performance. BRRI dhan98 consistently recorded the highest BLUE and BLUP values, followed by BRRI dhan75 and BRRI dhan85, whereas BRRI dhan48 and BRRI dhan82 remained the poorest performers.

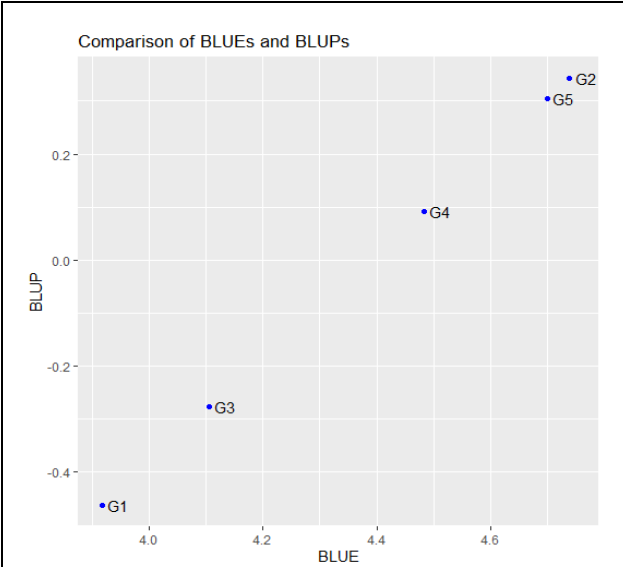


Fig. 6(A). Rangpur (E1)

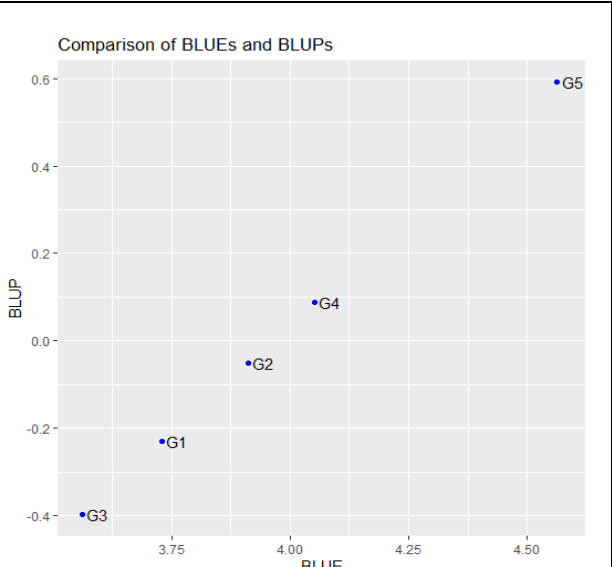


Fig. 6(B). Rajshahi (E2)

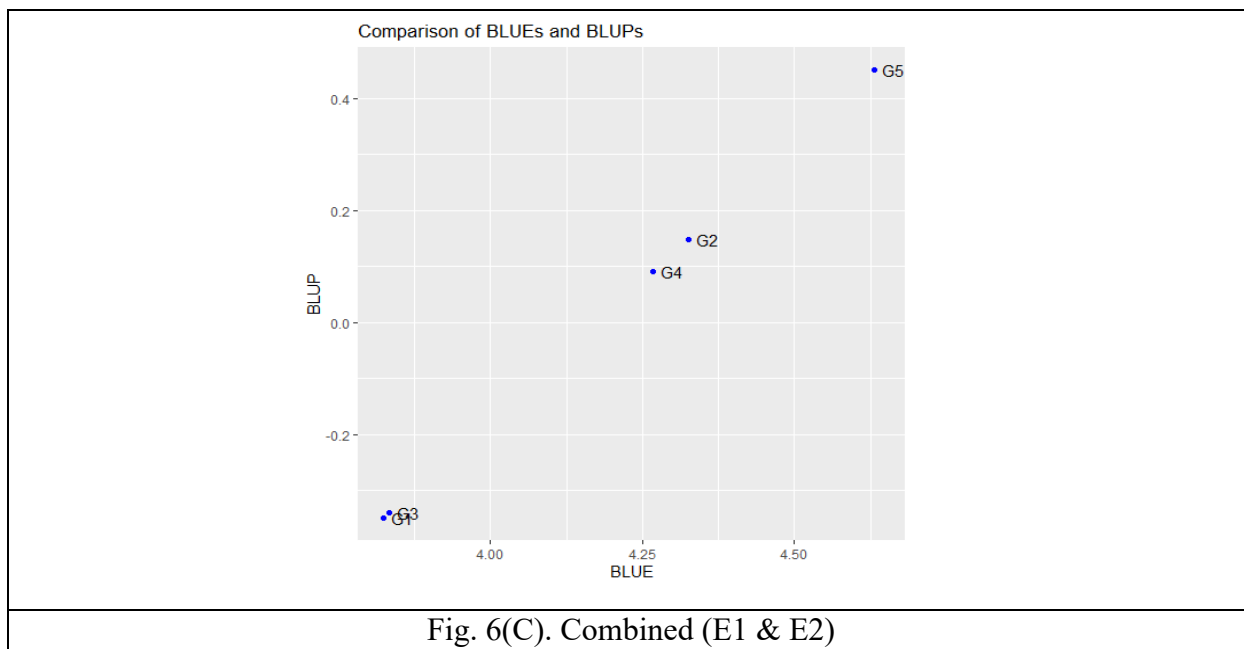


Fig. 6(C). Combined (E1 & E2)

Figure 6. Comparison of BLUEs and BLUPs for grain yield of the five genotypes across E1, E2, and Combined (E1 & E2). BLUEs = Best Linear Unbiased Estimators; BLUPs=Best Linear Unbiased Predictors; E1= Rangpur; E2= Rajshahi.

3.2 Yield Advantage

Analysis of the yield advantage (percent) (**Figure 7**) showed that although the production performance of the five varieties varied year and location-wise, BRRI dhan98 consistently showed the greatest advantage, reaching about 20% over the farmers' check and 10% over the benchmark in Rajshahi. In Rangpur, BRRI dhan75 remained competitive, whereas BRRI dhan82 generally showed negative yield advantages.

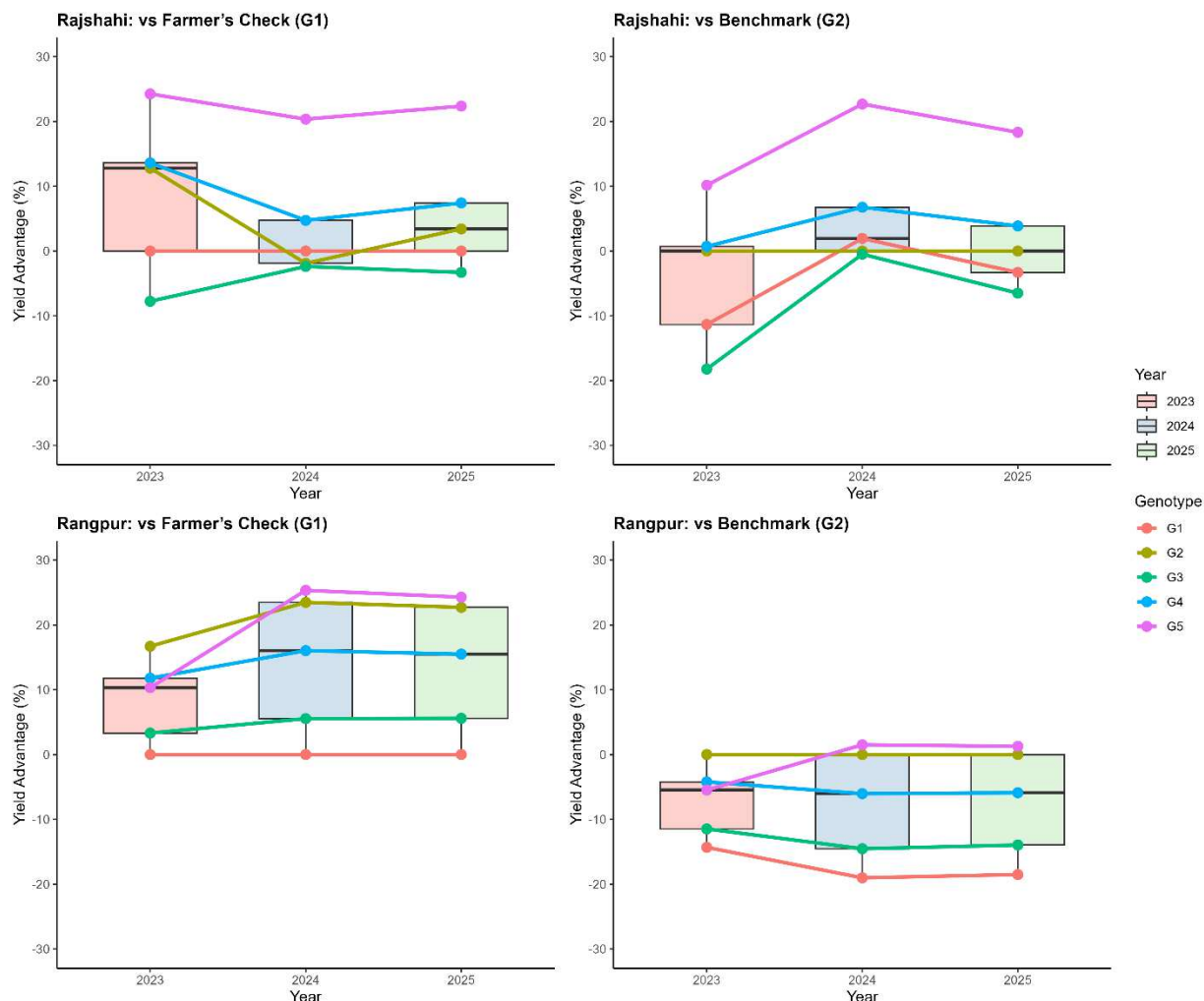


Figure 7. Comparison of the Yield Advantage (%) of the genotypes in E1 and E2. G1=BRRI dhan48; G2=BRRI dhan75; BRRI dhan82; G4=BRRI dhan85; G5=BRRI dhan98; E1=Rangpur; E2=Rajshahi.

3.3. Gross return Advantage

Figure 8 presents the GRA (percent) of the five rice genotypes for each of the trial years (2023 to 2025) compared to the farmers' check G1 and benchmark G2. Gross return followed a pattern similar to grain yield. BRRI dhan75 generated the highest returns in Rangpur, whereas BRRI dhan98 was the most profitable genotype in Rajshahi. BRRI dhan48 and BRRI dhan82 consistently produced the lowest returns.

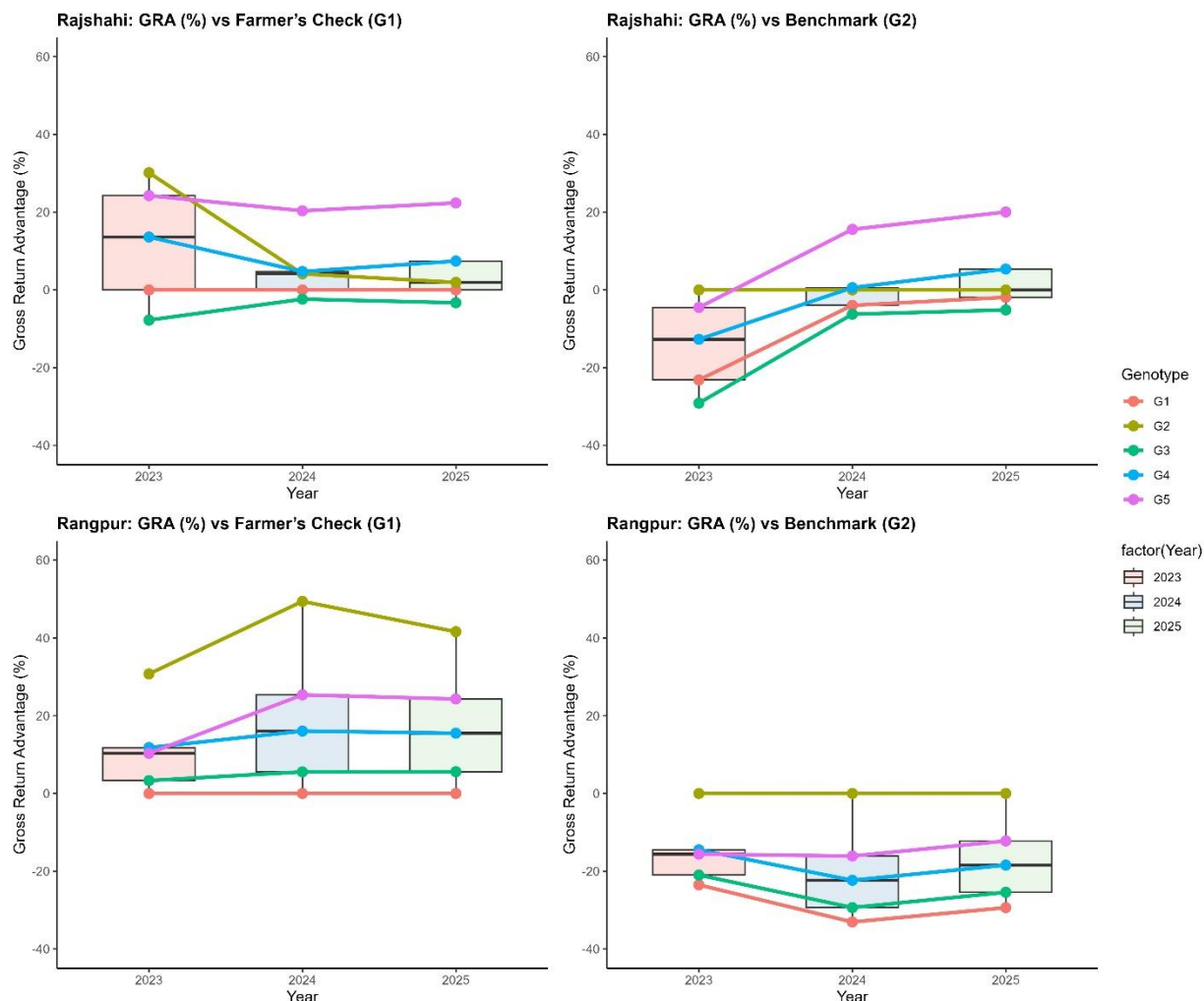


Figure 8. Comparison of the GRA (%) of the genotypes in E1 and E2. G1=BRRI dhan48; G2=BRRI dhan75; BRRI dhan82; G4=BRRI dhan85; G5=BRRI dhan98; E1=Rangpur; E2=Rajshahi.

3.4. Benefit-Cost Ratio

This heat map on BCR in **Figure 9** depicts a comparative picture of E1 (Rangpur) and E2 (Rajshahi) locations for 2023-2025 for the five genotypes. The darker the color, the higher the BCR (economically more profitable), and a lighter color indicates a lower BCR. In Rangpur, BRRI dhan75 and BRRI dhan98 consistently achieved the highest BCR, whereas profitability in Rajshahi declined after 2023 for all genotypes. Nevertheless, BRRI dhan98 maintained the highest overall BCR.



Figure 9. Benefit-Cost Ratio of the five rice genotypes evaluated under DSR systems in *Aus* 2023, 2024, and 2025 across E1 and E2. G1=BRRI dhan48; G2=BRRI dhan75; BRRI dhan82; G4=BRRI dhan85; G5=BRRI dhan98; E1=Rangpur; E2=Rajshahi.

3.5. Greenhouse Gas Intensity

A comparative analysis of GHGI for the five rice varieties across E1 and E2 locations is illustrated in **Figure 10**, including the overall GHGI results for the three experimental years. BRRI dhan98 consistently recorded the lowest GHGI, whereas BRRI dhan48 and BRRI dhan82 had the highest values. GHGI was generally higher in Rangpur than in Rajshahi, indicating a stronger location effect (climate, soil, and crop management conditions) on emission intensity.

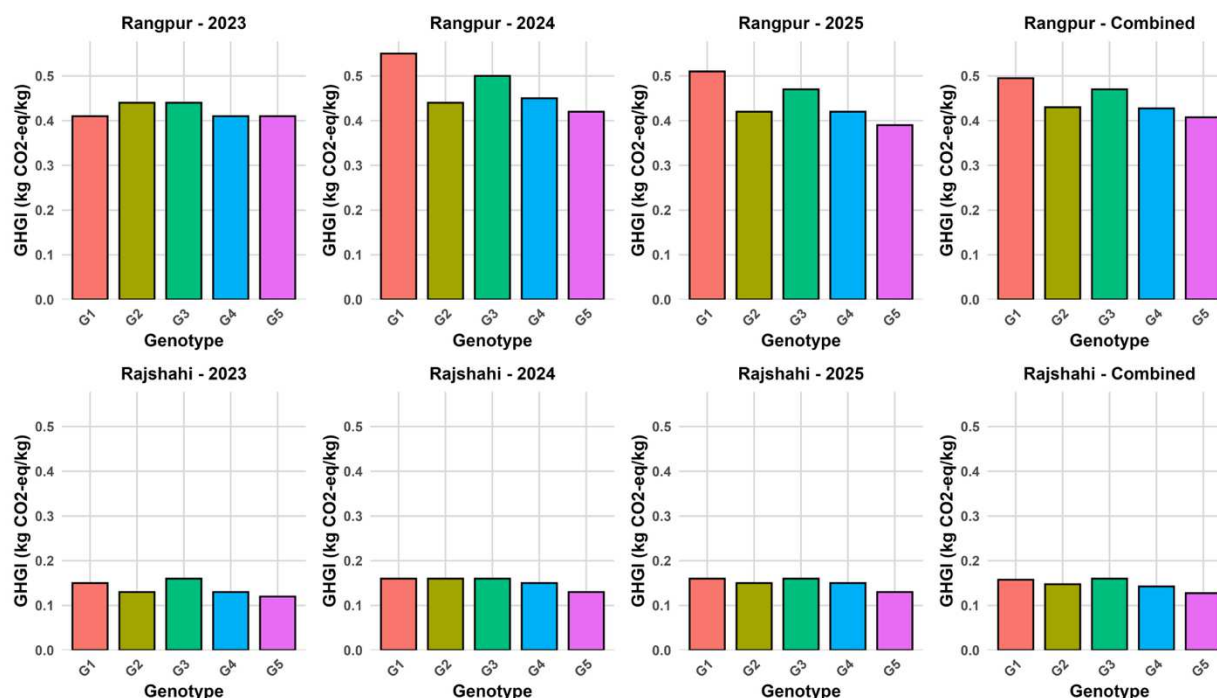


Figure 10. GHGI of the five rice genotypes evaluated under DSR systems in *Aus* 2023, 2024, and 2025 across E1 and E2. G1=BRRI dhan48; G2=BRRI dhan75; BRRI dhan82; G4=BRRI dhan85; G5=BRRI dhan98; E1=Rangpur; E2=Rajshahi.

4. Discussion

The study explains and illustrates the genotypic differences in grain yield, canopy coverage, and harvest duration of *Aus* rice under DSR across different environments in northern Bangladesh. BRRI dhan98 outperformed other candidates and checks, with the highest mean and predicted yields in both E1 and E2 locations. The BLUEs and BLUP analyses confirm its superiority, which indicates strong adaptability and positive genetic potential that align with high-yielding genotypes often combined with favorable agronomic traits and broad adaptability across environments, as reported earlier by **Gauch (2006)** and **Bocianowski et al. (2024)**. In contrast, BRRI dhan48 and BRRI dhan82 were consistently low yielding, with negative BLUP values confirming their limited suitability for DSR. Genotypes such as the benchmark variety BRRI dhan75 and candidate BRRI dhan85 showed relatively stable performance. BRRI dhan85 exhibited the lowest coefficient of variation, suggesting more consistent performance across environments despite not achieving the highest mean grain yield. However, the AMMI analysis confirmed significant GEI for grain yield and canopy coverage. This emphasizes the importance of considering both mean performance and stability when recommending varieties for diverse agro-ecologies (**Yan & Kang, 2002; Samonte et al., 2005; Tena et al., 2019**). The findings confirm that selection of varieties under DSR is

critical for farmers' success, and genetics continues to play a vital role for advantages in yield and gross returns.

Canopy coverage and harvest duration exhibit a significant variation among genotypes and across environments. Rapid canopy coverage helps farmers to reduce the cost of production by suppressing weed growth through its allelopathic effect, and early harvest helps to capture the early market segment for higher profit. Agricultural productivity increases due to this enhanced ground cover's ability to improve soil moisture retention and nutrient use efficiency. Additionally, ground cover increases soil moisture retention and decreases the frequency with which herbicides must be applied, which decreases input costs and herbicide use. Greater variability was observed in the E1 location compared to E2 for canopy coverage, suggesting environmental influence in E1. Stability analysis for canopy coverage found BRRI dhan75 as the most stable genotype, while BRRI dhan85 and BRRI dhan98, though high in coverage, reflected environment-specific adaptation (Yan et al., 2000).

From an economic perspective, BRRI dhan98 provided the highest yield advantage, gross returns advantage, and benefit-cost ratio in Rajshahi (E2). However, benchmark BRRI dhan75 scored better in Rangpur (E1). BRRI dhan75 has the advantage of consumers' preference in the E1 location because of its slender grain quality and mild aroma as compared to the coarse-grained BRRI Dhan 98. The preference for these traits fetched better prices for the farmers, which reflected in the GRA and BCR. In E2, grain yield is a priority, and BRRI Dhan 98 is a clear choice because of its consistently high yield and good economic returns. Region-specific recommendations and adaptive management strategies are a critical issue, and performance, stability, and economic benefit can be given special consideration. The adoption of DSR is complicated by the genotype-environment interaction, and scaling of DSR should focus on large-scale multi-environment trials to further dissect the physiological basis of the stability.

In addition to reducing performance variability within specific agro-ecological zones, it is important to determine site-specific suitable varieties and management practices. Increased reliance on data-based decision systems and farmer participatory trials will contribute to the increased reliability and wider adoption of DSR technologies. The yield advantage and economic benefit of BRRI dhan98 and BRRI dhan75 are favorably better than those of other genotypes, which aligns with previous studies showing that high-yielding, stable genotypes maximize farmer returns under direct-seeded rice systems (Yang et al., 2024).

The study has provided comparative evidence of GHG emissions mitigation through the choice of an appropriate cultivar. Direct seeding in rice cultivation requires less time and less water, and BRRI dhan98 combines high yield with relatively low greenhouse gas intensity, an added benefit to growers and the environment. By contrast, BRRI dhan48 and BRRI dhan82 exhibited higher emission intensities, reducing climatic sustainability and exacerbating climate change. The wide range of yield advantage across test years and locations, particularly in 2023 in E1 and in 2024

and 2025 in E2, should also be considered when recommending varieties to growers. Analyses like these provide clear evidence of what farmers may expect, highlighting the impact of genetics and environment and the requirements for testing them in farmers' fields.

The comparison of economic benefit and gas emissions in this study reinforces the importance of integrating climate-smart practices with genotype selection (**Maniruzzaman et al., 2025**). Direct-seeded rice farming system in Bangladesh provides opportunities to reduce labor and water inputs, and with proper varietal choice can boost productivity, profitability, and environmental sustainability. Studies like this one provide the necessary evidence to continue to pursue scaling the DSR system. Overall, the study figured out BRRI dhan98 as the most promising genotype, considering high yield, economic advantage, and relatively favorable GHG footprint. BRRI dhan85 is a stable alternative with moderate yield and profitability, while BRRI dhan75 has strong site-specific adaptation to the E1 location. Conversely, BRRI dhan48 and BRRI dhan82 underperformed, suggesting limited suitability for direct-seeded *Aus* systems.

The comparison of economic benefit and gas emissions in this study reinforces the importance of integrating climate-smart practices with genotype selection (**Maniruzzaman et al., 2025**). Overall, the study figured out BRRI dhan98 as the most promising genotype, considering high yield, economic advantage, and relatively favorable GHG footprint. BRRI dhan85 is a stable alternative with moderate yield and profitability, while BRRI dhan75 has strong site-specific adaptation to the E1 location. Conversely, BRRI dhan48 and BRRI dhan82 underperformed, suggesting limited suitability for direct-seeded *Aus* systems.

5. Limitations

Although the present study details the benefits of direct-seeded rice systems - improving productivity, profitability, and environmental sustainability- there are limitations to the experiments. First, the findings are based on limited-location and short-term evaluations, which may not fully capture the variability in climatic conditions, soil characteristics, pest and disease dynamics, and management practices across the diverse agro-ecological regions of Bangladesh. Long-term and multi-location trials are therefore essential to evaluate yield stability, adaptability, weed competitiveness, and resilience of DSR-compatible rice varieties under changing climatic conditions.

Second, weed infestation remains one of the major constraints to successful DSR adoption. While the study considered overall system performance, more detailed investigation is required to develop effective, economically viable, and environmentally sustainable weed management approaches, particularly integrated weed management strategies suitable for different production environments.

Third, the study did not comprehensively address several operational challenges associated with DSR, including uneven crop establishment, limitations in mechanization, and variability in farmer-level management practices. These factors can significantly influence field performance and adoption outcomes under real farming conditions.

6. Conclusions

Direct-seeded rice cultivation offers a promising pathway for improving the sustainability of rice production systems reducing labor and water requirements while enhancing productivity, profitability, and environmental performance. The present study provides evidence supporting the potential of DSR-based cultivation systems for sustainable agricultural intensification in Bangladesh.

Among the evaluated genotypes, BRRI dhan98 emerged as the most suitable candidate for sustainable DSR cultivation due to its superior yield performance, higher gross return, favorable benefit-cost ratio, and lower greenhouse gas emission intensity. These attributes make the variety well aligned with the goals of low-carbon and resource-efficient rice production systems in Bangladesh. BRRI dhan75 also demonstrated stable economic and environmental performance, particularly under the agro-ecological conditions of the Rangpur region. In contrast, the comparatively poor performance of BRRI dhan48 indicates the necessity of replacing older, input-inefficient varieties with modern cultivars better adapted to sustainable DSR systems.

To ensure successful scaling of DSR technology, region-specific varietal selection and validation should be prioritized considering the diverse soil, rainfall, and temperature conditions across Bangladesh. In parallel, strengthening integrated weed management practices, improving access to DSR-compatible machinery, promoting farmer skill development, and implementing supportive policy incentives will be critical for achieving sustainable and widespread adoption of DSR systems in the future.

Statements

Data availability statement

The author(s) will make the raw data, supporting the findings of this study, available upon request, without undue reservation.

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Ethics, Consent to Participate, and Consent to Publish declarations

The above declarations are not applicable

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funding organizations had no role in the study design, data collection, data analysis, interpretation of the results, manuscript preparation, or the decision to publish.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

References

1. Agro-Ecological Zones (AEZs) maps. (n.d.). *BAEZ maps*.
<https://www.bamis.gov.bd/en/page/aezs-maps/>

2. Ahmed, S., Alam, M. J., Hossain, A., Islam, A. K. M. M., Awan, T. H., Soufan, W., Qahtan, A. A., Okla, M. K., & El Sabagh, A. (2021). Interactive effect of weeding regimes, rice cultivars, and seeding rates on rice–weed competition under dry direct-seeded conditions. *Sustainability*, 13(1), 317. <https://doi.org/10.3390/su13010317>

3. Ahmed, S., Humphreys, E., & Chauhan, B. S. (2016). Optimum sowing date and cultivar duration of dry-seeded boro on the High Ganges River Floodplain of Bangladesh. *Field Crops Research*, 190, 91–102. <https://doi.org/10.1016/j.fcr.2015.12.004>

4. Ahmed, S., Kumar, V., Zaman, A. U., Dewan, M. R., Khatun, A., Hossain, K., Singh, S., Timsina, J., & Krupnik, T. J. (2025). Dry direct-seeded and broadcast rice: A profitable and climate-smart alternative to puddled transplanted Aus rice in Bangladesh. *Field Crops Research*, 322, 109739. <https://doi.org/10.1016/j.fcr.2025.109739>

5. Ahmed, T. (2025). *Grain and feed update: Bangladesh* (GAIN Report No. BG2025-0016). In E. Covert (Ed.), *USDA Foreign Agricultural Service*. <https://www.fas.usda.gov/>

6. Akter, T., Afrad, M. S. I., Habib, M. A., Zhang, Y., Sarkar, M. A. R., Nayak, S., et al. (2025). Farmers' adoption of newly released climate-resilient rice varieties in the coastal ecosystem of

- 556 Bangladesh: Effectiveness of a head-to-head adaptive trial. *Food and Energy Security*, 14,
557 e70075. <https://doi.org/10.1002/fes3.70075>
- 558 7. Alliance of Bioversity International & CIAT. (n.d.). *TRICOT (Triadic Comparisons of*
559 *Technologies)*. [https://alliancebioversityciat.org/tools-innovations/tricot-triadic-comparisons-](https://alliancebioversityciat.org/tools-innovations/tricot-triadic-comparisons-technologies)
560 [technologies](https://alliancebioversityciat.org/tools-innovations/tricot-triadic-comparisons-technologies)
- 561 9. Asian Development Bank. (2010). *The changing role of rice in Asia's food security*
562 (Sustainable Development Working Paper No. 15). Asian Development Bank. [ADB working](#)
563 [paper](#)
- 564 10. Atlin, G. N., Baker, R. J., McRae, K. B., & Lu, X. (2000). Selection response in subdivided
565 target regions: Mixed-model estimation and BLUP. *Crop Science*, 40(1), 7–13.
566 <https://doi.org/10.2135/cropsci2000.4017>
- 567 11. Bandumula, N. (2018). Rice production in Asia: Key to global food security. *Proceedings of*
568 *the National Academy of Sciences, India Section B: Biological Sciences*, 88, 1323–1328.
569 <https://doi.org/10.1007/s40011-017-0867-7>
- 570 12. Bangladesh Agricultural Research Council. (2012). *Land and soil resource utilization guide*
571 *(AEZ database of Bangladesh)*. Ministry of Agriculture, Government of the People's Republic of
572 Bangladesh. <https://barc.gov.bd/pages/notices/6922f0f2dbfbab28ce0d2012>
- 573 13. Bangladesh Bureau of Statistics. (2023). *Yearbook of agricultural statistics 2023*. Ministry of
574 Planning, Government of the People's Republic of Bangladesh. [https://bbs.gov.bd/pages/static-](https://bbs.gov.bd/pages/static-pages/6922e0d6933eb65569e28cbf)
575 [pages/6922e0d6933eb65569e28cbf](https://bbs.gov.bd/pages/static-pages/6922e0d6933eb65569e28cbf)
- 576 14. Bangladesh Bureau of Statistics. (2024). *Yearbook of agricultural statistics 2024*. Ministry of
577 Planning, Government of the People's Republic of Bangladesh. [https://bbs.gov.bd/pages/static-](https://bbs.gov.bd/pages/static-pages/6922e0d6933eb65569e28cbf)
578 [pages/6922e0d6933eb65569e28cbf](https://bbs.gov.bd/pages/static-pages/6922e0d6933eb65569e28cbf)
- 579 15. Bangladesh Meteorological Department. (2025). *Bangladesh Meteorological Department*.
580 <https://server6.bmd.gov.bd/>
- 581 Bangladesh Rice Research Institute. (2023). *BRRI at a glance 2023*. Bangladesh Rice Research
582 Institute. [https://objectstorage.ap-dcc-gazipur-](https://objectstorage.ap-dcc-gazipur-1.oraclecloud15.com/n/axvjbnqprylg/b/V2Ministry/o/office-brri/2024/12/4f95ca640dc248c0aaa24e33c60cd0a7.pdf)
583 [1.oraclecloud15.com/n/axvjbnqprylg/b/V2Ministry/o/office-](https://objectstorage.ap-dcc-gazipur-1.oraclecloud15.com/n/axvjbnqprylg/b/V2Ministry/o/office-brri/2024/12/4f95ca640dc248c0aaa24e33c60cd0a7.pdf)
584 [brri/2024/12/4f95ca640dc248c0aaa24e33c60cd0a7.pdf](https://objectstorage.ap-dcc-gazipur-1.oraclecloud15.com/n/axvjbnqprylg/b/V2Ministry/o/office-brri/2024/12/4f95ca640dc248c0aaa24e33c60cd0a7.pdf)
- 585 17. Bari, L., & Ahmed, S. (2018). Performance of Aus rice under different tillage systems and
586 crop establishment methods in southwest Bangladesh. *Journal of Experimental Sciences*, 9, 5–9.
- 587 18. Bocianowski, J., Nowosad, K., & Rejek, D. (2024). Genotype × environment interaction for
588 grain yield in maize (*Zea mays* L.) using the additive main effects and multiplicative interaction
589 (AMMI) model. *Journal of Applied Genetics*, 65, 653–664. [https://doi.org/10.1007/s13353-024-](https://doi.org/10.1007/s13353-024-00899-4)
590 [00899-4](https://doi.org/10.1007/s13353-024-00899-4)

- 591 **19.** Ceccarelli, S., Guimarães, E. P., & Weltzien, E. (2009). *Plant breeding and farmer*
592 *participation*. Food and Agriculture Organization of the United Nations.
- 593 **20.** Chaudhary, A., Venkatramanan, V., Mishra, A. K., & Sharma, S. (2022). Agronomic and
594 environmental determinants of direct-seeded rice in South Asia. *Circular Economy and*
595 *Sustainability*, 3, 253–272. <https://doi.org/10.1007/s43615-022-00168-0>
- 596 **21.** Debsharma, S. K., Rahman, M. A., Khatun, M., Disha, R. F., Jahan, N., Quddus, M. R., et al.
597 (2024). Developing climate-resilient rice varieties (BRRI dhan97 and BRRI dhan99) suitable for
598 salt-stress environments in Bangladesh. *PLoS ONE*, 19, e0294573.
599 <https://doi.org/10.1371/journal.pone.0294573>
- 600 **22.** Food and Agriculture Organization of the United Nations. (2025). *Cereal supply and demand*
601 *brief: May 2025*. <https://www.fao.org/>
- 602 **23.** Gaihre, Y. K., Islam, S. M., & Singh, U. (2025). Managing rice soils for mitigating
603 greenhouse gas emissions. In *Agriculture toward net zero emissions* (pp. 305–326). Academic
604 Press.
- 605 **24.** Gaihre, Y. K., Singh, U., Islam, S. M., Huda, A., Islam, M. R., Satter, M. A., et al. (2015).
606 Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in
607 Bangladesh. *Geoderma*, 259–260, 370–379. <https://doi.org/10.1016/j.geoderma.2015.06.010>
- 608 **25.** Gauch, H. G., Jr. (1992). *Statistical analysis of regional yield trials: AMMI analysis of*
609 *factorial designs*. Elsevier Science Publishers.
- 610 **26.** Gauch, H. G., Jr. (2006). Statistical analysis of yield trials by AMMI and GGE. *Crop*
611 *Science*, 46, 1488–1500. <https://doi.org/10.2135/cropsci2005.07-0193>
- 612 **27.** Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd
613 ed.). John Wiley & Sons.
- 614 **28.** Henderson, C. R. (1975). Best linear unbiased estimation and prediction under a selection
615 model. *Biometrics*, 31(2), 423–447. <https://doi.org/10.2307/2529430>
- 616 **29.** Islam, S. F. U., Sander, B. O., Quilty, J. R., de Neergaard, A., van Groenigen, J. W., &
617 Jensen, L. S. (2020). Mitigation of greenhouse gas emissions and reduced irrigation water use in
618 rice production through water-saving irrigation scheduling, reduced tillage and fertiliser
619 application strategies. *Science of the Total Environment*, 739, 140215.
620 <https://doi.org/10.1016/j.scitotenv.2020.140215>
- 621 **30.** Islam, S. M., Gaihre, Y. K., Biswas, J. C., Singh, U., Ahmed, M. N., Sanabria, J., & Saleque,
622 M. A. (2018). Nitrous oxide and nitric oxide emissions from lowland rice cultivation with urea
623 deep placement and alternate wetting and drying irrigation. *Scientific Reports*, 8, 17623.
624 <https://doi.org/10.1038/s41598-018-35955-7>

- 625 **31.** Liu, Y. (2022). *Characterizing methane (CH₄) and carbon dioxide (CO₂) emissions through*
626 *mobile platforms from local to national scale* (Doctoral dissertation). Université Paris-Saclay &
627 The Cyprus Institute.
- 628 **32.** Maniruzzaman, M., Biswas, J. C., Hossain, M. B., Mainuddin, M., Roy, D., Yesmin, M. S.,
629 et al. (2025). Greenhouse gas emissions from dry season rice irrigation in Bangladesh. *Mitigation*
630 *and Adaptation Strategies for Global Change*, 30, 8. [https://doi.org/10.1007/s11027-024-10159-](https://doi.org/10.1007/s11027-024-10159-z)
631 [z](https://doi.org/10.1007/s11027-024-10159-z)
- 632 **33.** Mohidem, N. A., Hashim, N., Shamsudin, R., & Che Man, H. (2022). Rice for food security:
633 Revisiting its production, diversity, rice milling process, and nutrient content. *Agriculture*, 12,
634 741. <https://doi.org/10.3390/agriculture12060741>
- 635 **34.** Nayak, S., Habib, M. A., Iftekharuddaula, K. M., & Kabir, M. H. (Eds.). (2022). *National*
636 *level result sharing and planning of head-to-head adaptive trials in Bangladesh*. International
637 Rice Research Institute. <http://books.irri.org/HHAT-Workshop-Report.pdf>
- 638 **35.** Paswan, S. K., Sharma, V., Singh, V. K., & Ahmad, A. (2014). Genetic variability studies for
639 yield and related attributes in rice genotypes (*Oryza sativa* L.). *Research Journal of Agricultural*
640 *Sciences*, 5, 750–752.
- 641 **36.** Piepho, H. P., Möhring, J., Melchinger, A. E., & Büchse, A. (2008). BLUP for phenotypic
642 selection in plant breeding and variety testing. *Euphytica*, 161, 209–228.
643 <https://doi.org/10.1007/s10681-007-9449-8>
- 644 **37.** Rad, M. N., et al. (2013). Genotype × environment interaction by AMMI and GGE biplot
645 analysis in three consecutive generations of wheat under normal and drought stress. *Australian*
646 *Journal of Crop Science*, 7, 956–961.
- 647 **38.** Rahman, M. M. (2019). Potential benefits of dry direct-seeded rice culture: A review.
648 *Fundamental and Applied Agriculture*, 4, 744–758. <https://doi.org/10.5455/faa.24517>
- 649 **39.** Robinson, G. K. (1991). That BLUP is a good thing: The estimation of random effects.
650 *Statistical Science*, 6(1), 15–51. <https://doi.org/10.1214/ss/1177011926>
- 651 **40.** Samonte, S. O. P., Wilson, L. T., McClung, A. M., & Medley, J. C. (2005). Targeting
652 cultivars onto rice-growing environments using AMMI and SREG GGE biplot analyses. *Crop*
653 *Science*, 45, 2414–2424. <https://doi.org/10.2135/cropsci2004.0627>
- 654 **41.** SECTOR tool. (n.d.). *Source-selective and emission-adjusted greenhouse gas calculator*.
655 <https://ghgmitigation.irri.org/resources/mrv-toolbox/sector>
- 656 **42.** Tena, E., et al. (2019). Genotype × environment interaction for sugar yield in three crop
657 cycles of sugarcane clones in Ethiopia. *Cogent Food & Agriculture*, 5, 1651925.
658 <https://doi.org/10.1080/23311932.2019.1651925>

43. van Etten, J., Manners, R., Steinke, J., Matthus, E., de Sousa, K., & Fadda, C. (2019). First experiences with a novel farmer citizen science approach: Crowdsourcing participatory variety selection through on-farm triadic comparisons of technologies (TRICOT). *Experimental Agriculture*, 55(S1), 275–296. <https://doi.org/10.1017/S0014479716000739>
44. Ward, J. H., Jr. (1963). Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association*, 58, 236–244. <https://doi.org/10.1080/01621459.1963.10500845>
45. Yan, W., & Kang, M. S. (2002). *GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists* (1st ed.). CRC Press. <https://doi.org/10.1201/9781420040371>
46. Yan, W., Hunt, L. A., Sheng, Q., & Szlavnics, Z. (2000). Cultivar evaluation and mega-environment investigation based on the GGE biplot. *Crop Science*, 40, 597–605. <https://doi.org/10.2135/cropsci2000.403597x>
47. Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., et al. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions, and improves soil health. *Nature Communications*, 15, 198. <https://doi.org/10.1038/s41467-023-44464-9>

Supplementary Tables

Trait	Statistic	Location	BRRI dhan48 (farmers' check)	BRRI dhan75 (benchmark)	BRRI dhan82 (test variety)	BRRI dhan85 (test variety)	BRRI dhan98 (test variety)
GY	Mean	E1	3.92	4.74	4.11	4.48	4.70
		E2	3.73	3.91	3.56	4.05	4.56
		Combined (E1 & E2)	3.82	4.33	3.83	4.27	4.63
	SD	E1	0.41	0.27	0.31	0.17	0.43
		E2	0.20	0.37	0.25	0.35	0.29
		Combined (E1 & E2)	0.33	0.53	0.39	0.35	0.37
	Min	E1	3.39	4.42	3.64	4.18	3.77
		E2	3.36	3.40	3.19	3.46	4.07
		Combined (E1 & E2)	3.36	3.40	3.19	3.46	3.77
	Max	E1	4.69	5.26	4.69	4.83	5.34
		E2	4.21	4.81	4.28	4.99	5.05

		Combined (E1 & E2)	4.69	5.26	4.69	4.99	5.34
	CV	E1	10.40	5.63	7.52	3.83	9.10
		E2	5.39	9.43	7.04	8.66	6.27
		Combined (E1 & E2)	8.72	12.10	10.2	8.19	7.94
CC	Mean	E1	91.5	90.6	90.8	89.8	90.6
		E2	86.6	86.2	78.6	87.4	87.3
		Combined (E1 & E2)	89	88.4	84.7	88.6	89
	SD	E1	2.75	3.37	3.57	3.93	3.56
		E2	4.24	4.29	4.59	4.67	4.25
		Combined (E1 & E2)	4.33	4.41	7.36	4.45	4.24
	Min	E1	86	83	83	81	85
		E2	78	81	71	81	81
		Combined (E1 & E2)	78	81	71	81	81
	Max	E1	97	97	96	97	98
		E2	96	95	89	97	98
		Combined (E1 & E2)	97	97	96	97	98
	CV	E1	3.01	3.72	3.94	4.38	3.93
		E2	4.9	4.98	5.84	5.35	4.87
		Combined (E1 & E2)	4.87	4.99	8.7	5.02	4.76
HD	Mean	E1	108	109	105	104	104
		E2	106	105	105	106	105
		Combined (E1 & E2)	107	107	105	105	104
	SD	E1	7.79	5.5	6.49	5.31	5.31
		E2	1.95	2.29	1.99	2.87	2.56
		Combined (E1 & E2)	5.73	4.65	4.76	4.32	4.18
	Min	E1	97	102	97	97	97
		E2	101	101	101	99	98
		Combined (E1 & E2)	97	101	97	97	97
	Max	E1	116	116	116	111	111

		E2	109	109	108	110	110
		Combined (E1 & E2)	116	116	116	111	111
	CV	E1	7.24	5.03	6.18	5.11	5.11
		E2	1.85	2.18	1.89	2.72	2.43
		Combined (E1 & E2)	5.38	4.34	4.53	4.13	4

Table 1. Descriptive statistics for grain yield, canopy coverage, and harvest duration of rice genotypes at E1 & E2

Source	Location	df	Grain Yield	Canopy Coverage	Harvest Duration
ENV	E1	2	1.15**	580.96**	3056.36**
	E2	2	1.68**	15.14	44.29*
	Combined (E1 & E2)	5	4.39**	767.65**	1246.50**
REP (ENV)	E1	33	0.04	11.60**	6.09**
	E2	33	0.07	19.35	9.59**
	Combined (E1 & E2)	66	0.06	15.48*	7.84**
GEN	E1	4	4.78**	13.49**	204.09**
	E2	4	5.28**	505.18**	1.58
	Combined (E1 & E2)	4	8.64**	244.79**	102.76**
GEN x ENV	E1	8	0.19	3.98	21.52**
	E2	8	0.28**	32.45	12.59**
	Combined (E1 & E2)	20	0.47**	69.35**	34.23**
PC1	E1	5	0.31*	6.32	34.44**
	E2	5	0.45**	49.06*	19.65**
	Combined (E1 & E2)	8	0.79**	139.25**	57.20**
PC2	E1	3	0.00	0.08	0.00
	E2	3	0.00	4.77	0.83
	Combined (E1 & E2)	6	0.40**	42.43**	25.49**
PC3	Combined (E1 & E2)	4	0.19	2.78	18.15**

PC4	Combined (E1 & E2)	2	0.00	3.68	0.69
Residuals	E1	132	0.11	3.91	1.09
	E2	132	0.06	18.79	3.54
	Combined (E1 & E2)	264	0.08	11.35	2.32
Total	E1	187	0.21	11.65	40.74
	E2	187	0.21	30.42	5.78
	Combined (E1 & E2)	379	0.27	30.63	24.12

Table 2. ANOVA and AMMI Components for grain yield, canopy coverage, and harvest duration of rice genotypes
 ***= Significant at 0.1%; **= Significant at 1%; *=Significant at 5% probability level; df= Degrees of freedom; REP = Replication, PC = Principal Component

Supplementary Files

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- [Tables.docx](#)