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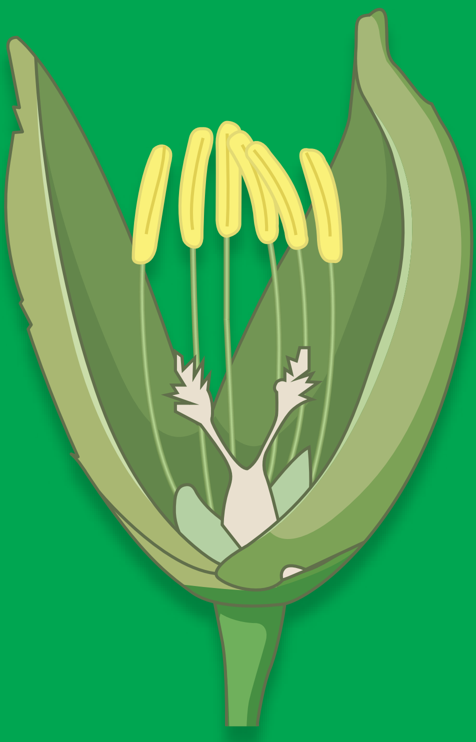

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CONTENTS

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Selection of Stable High-yielding Fine Grain Rice (*Oryza sativa* L.) Genotypes Using AMMI, WAASB, and Multi-Trait Stability Indices

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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

Fine-grain rice is highly preferred by consumers due to its superior cooking quality and higher market price. Consequently, the Bangladesh Rice Research Institute (BRRI) has developed several fine-grain rice genotypes through its breeding programs. This study evaluated the yield performance and stability of nine advanced fine-grain rice lines along with two local cultivars and five released varieties across ten agro-ecological zones during the 2023–24 Boro season. Genotype–environment interaction (GEI) for grain yield (GY) and yield-related traits was analyzed using the Additive Main Effects and Multiplicative Interaction (AMMI) model, the Weighted Average of Absolute Scores and Yield (WAASBY) index, and the Multi-Trait Stability Index (MTSI). Combined analysis of variance revealed that genotype, environment, and GEI significantly influenced grain yield and its components. Most traits exhibited moderate to high heritability (0.74–0.97) with selection accuracy above 80%, indicating strong genetic control. Among the tested genotypes, BR17-23-8-2-7B (G6) recorded the highest mean yield, while Bhanga, Faridpur (E3) was identified as the most favorable environment. Stability analyses indicated that G6 ranked highest based on WAASBY (91.45), whereas BRH11-7-17-10B (G7) and BRH9-3-2B (G8) were identified as the most stable genotypes according to MTSI. Overall, G6, G7, and G8 showed superior performance compared with the local and released varieties, suggesting their potential for cultivation and use in breeding programs targeting diverse agro-ecological environments.

1. Introduction

Fine-grain rice (*Oryza sativa* L.) plays an important role in global rice production, particularly in Asia, where it is highly valued for its aesthetic appearance, cooking quality, and suitability for regional dietary preferences (Custodio et al., 2019). These varieties are characterized by slender grains and relatively high amylose content, producing long and non-sticky cooked rice, which is widely preferred in many South Asian countries, including Bangladesh (Custodio et al., 2016; Alam et al., 2024). Due to their superior grain quality and higher market value, the demand for fine-grain rice is steadily increasing in both domestic and international markets. Consequently, rice breeding programs are increasingly focusing on improving not only grain quality but also yield potential.

However, rice production in Bangladesh faces

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significant challenges due to climate change. Rising temperatures and irregular precipitation patterns are expected to adversely affect rice productivity, particularly through heat and drought stress during critical growth stages (Rahman et al., 2024). These stresses can severely reduce crop yield and threaten national food security. To address these challenges, the Bangladesh Rice Research Institute (BRRI) has played a leading role in developing climate-resilient and high-yielding fine-grain rice varieties. Between 2002 and 2022, several improved fine-grain rice varieties were released, including BRRI dhan81, BRRI dhan88, and BRRI dhan104.

Despite these advances, the performance of rice genotypes often varies considerably across different environments due to genotype × environment interaction (GEI). Variations in soil properties, climate, and management practices across regions can significantly influence yield performance and stability. Therefore, multi-environment trials (METs) are essential for evaluating genotype adaptability and identifying stable and high-performing cultivars across diverse agro-ecological conditions.

Several statistical approaches have been widely used to analyze GEI and genotype stability in METs. Among them, the Additive Main Effects and Multiplicative Interaction (AMMI) model, the Weighted Average of Absolute Scores Biplot (WAASB), and the Multi-Trait Stability Index (MTSI) are commonly applied to evaluate genotype performance and stability across environments (Gauch, 1992; Gauch and Zobel 1996; Olivoto et al., 2019). While AMMI and WAASB primarily focus on yield stability, MTSI enables simultaneous selection of genotypes based on multiple traits, thereby improving the efficiency and accuracy of genotype selection in breeding programs.

Although several fine-grain rice varieties have been developed in Bangladesh, limited studies have comprehensively evaluated the stability and multi-trait performance of newly developed advanced lines across diverse agro-ecological zones. A clear understanding of genotype stability and adaptability under different environmental conditions is essential for identifying superior genotypes suitable for large-scale cultivation.

Therefore, the present study aimed to evaluate advanced fine-grain rice genotypes developed by the Bangladesh Rice Research Institute (BRRI) across multiple agro-ecological zones in Bangladesh during the 2023–2024 Boro season. Specifically, the study sought to assess genotype–environment interactions for grain yield and related traits and to identify stable and high-performing genotypes suitable for diverse environments.

2. Materials and methods

2.1. Experiment sites

The field experiment was conducted at ten locations representing major rice-growing regions of Bangladesh during the 2023–24 Boro season. The experimental sites were selected collaboratively by researchers from the Adaptive Research Division (ARD) and regional stations of the Bangladesh Rice Research Institute (BRRI). The geographical distribution of the study locations is presented in Fig. 1, which was prepared using QGIS version 3.38.3. Information on latitude, longitude, soil texture, and elevation of the experimental sites is provided in Table 1. Meteorological data, including average maximum temperature, relative humidity, and total rainfall during the growing period, were obtained from the Plant Physiology Division of the Bangladesh Rice Research Institute (BRRI) and the Bangladesh Meteorological Department (BMD). These climatic variables are illustrated in Fig. 2.

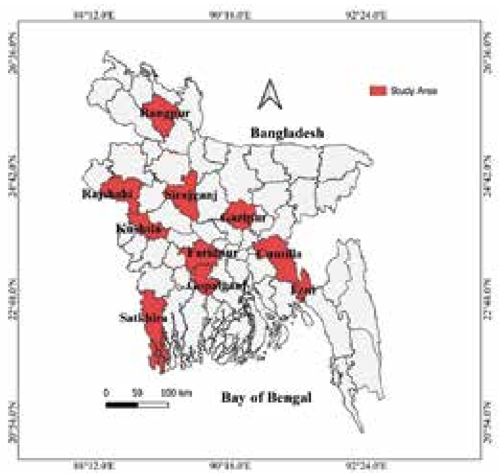

Fig. 1. Location of the study area in different districts of Bangladesh.

Table 1

Geographical, soil, and climatic characteristics of the ten environments used for multi-location trials of fine-grain rice during the 2023-24 Boro season.

Locations	Codes	Latitude	Longitude	Elevation (m)	Soil texture
Paba, Rajshahi	E1	24°43'57"N	88°66'22"E	17	Loam- clay
Sadar, Kushtia	E2	23°91'52"N	89°09'65"E	27	Clay-loam
Bhanga, Faridpur	E3	23°39'79"N	89°99'12"E	11	Clay loam-sandy loam
Kamarkhanda, Sirajganj	E4	24°39'42"N	89°63'74"E	13	Clay loam
Sadar, Satkhira	E5	22°73'07"N	88°98'69"E	3	Silty clay
Debidwar, Cumilla	E6	23°61'23"N	90°97'02"E	14	Grey loam - dark grey clay
Mithapukur, Rangpur	E7	25°52'13"N	89°30'19"E	34	Loam- clay loam
Sonagazi, Feni	E8	22°82'49"N	91°39'50"E	5	Silty loam-Clay loam
Sadar, Gopalganj	E9	22°96'08"N	89°82'15"E	3.1	Clay loam-sandy loam
Gazipur	E10	23°99'17"N	90°40'18"E	34	Silty clay loam

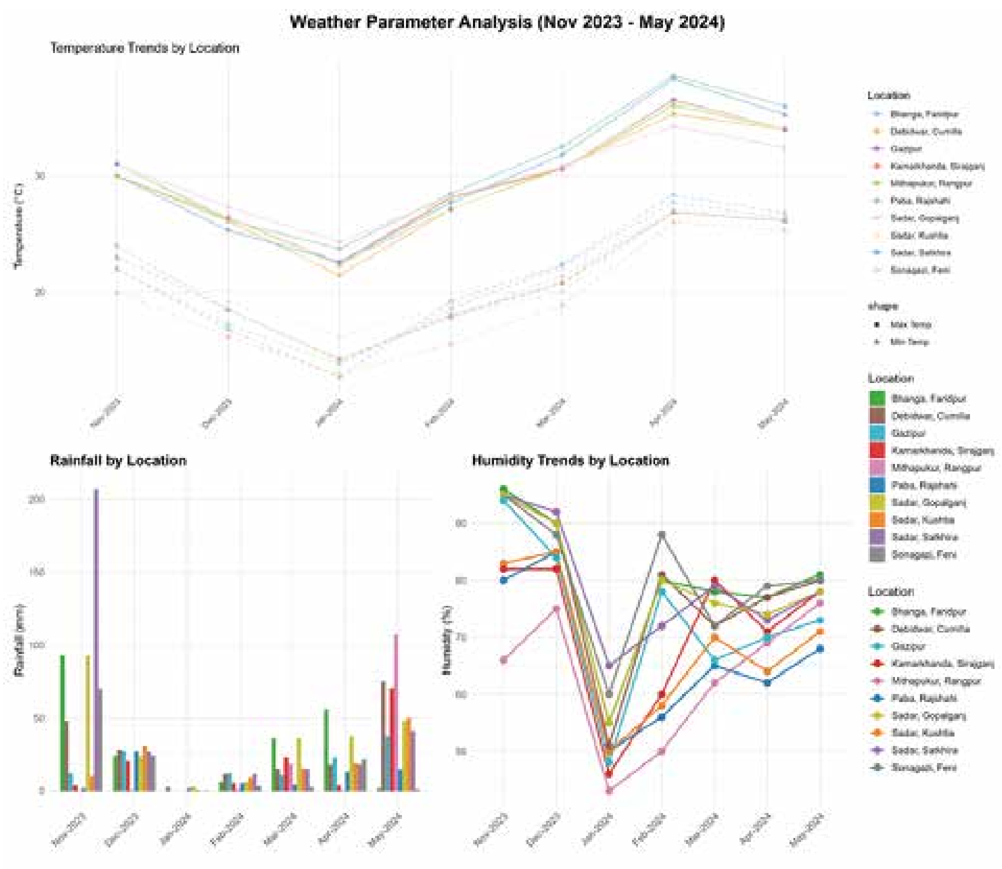

Fig. 2. Weather conditions of the selected regions during 2023-24 Boro season (a) Temperature 0C; (b) Total rainfall (mm); (c) Relative humidity (%).

2.2. Plant materials

Seeds of the genotypes along with their chemical and physical properties were received from the Plant Breeding Division (PBD), BRRI for evaluating yield potentiality and adaptability at farmers' field in different agro-ecological zones. Chemical and physical properties of the selected genotypes were analyzed except G4 and G14 at the Grain Quality and Nutrition (GQN) division, BRRI which are given in the Table 2.

Table 2
Chemical and physical properties of the genotypes.

Genotypes code	Alkali spreading value	Amylose content%	Protein content%	Elongation ratio	Imbibition ratio	Milling outturn%	Head rice yield%	L/B ratio	Size & shape
G1	6.9	25.7	8.1	1.5	3.9	70	57	3.3	LS
G2	3.2	25.0	8.1	1.5	4.8	70	56	3.3	LS
G3	7.0	25.4	8.0	1.7	4.8	69	61	3.4	LS
G4	-	-	-	-	-	-	-	-	MS
G5	5.2	24.0	7.1	1.4	3.9	71	56	3.6	MS
G6	4.1	19.2	8.2	1.5	4.3	72	60	3.0	MB
G7	3.7	19.1	7.7	1.4	3.9	72	60	3.0	MB
G8	3.6	19.0	7.6	1.4	4.3	72	62	3.1	MS
G9	3.7	19.1	7.3	1.5	4.5	72	59	3.0	MB
G10	3.1	25.4	7.7	1.4	4.3	70	61	3.1	LS
G11	3.6	25.0	8.1	1.6	4.8	62	60	2.8	SB
G12	7.0	27.0	9.0	1.4	4.3	62	43	3.3	LS
G13	7.0	27.1	8.6	1.4	3.9	70	56	4.5	Ex-LS
G14	-	-	-	-	-	-	-	-	LS
G15	4.8	26.0	9.8	1.3	4.5	71	60	3.1	LS
G16	4.2	25.6	9.0	1.4	4.7	69	43	3.4	LS

L/B Ratio: Length/Breadth Ratio, LS: Long Slender, Ex-LS: Extra-Long Slender, MS: Medium Slender, MB: Medium Bold, SB: Short Bold, G1: BR10645-6-4-8-1-2, G2: BR10646-3-2-2-4-3, G3: BR10648-12-1-3-4-1, G4: BRH15-24-7B, G5: BR9392-1-7-5B, G6: BR17-23-8-2-7B, G7: BRH11-7-17-10B, G8: BRH9-3-2B, G9: BRH13-9-5-2B, G10: Zira, Nachol, G11: Katari, Shibganj, G12: BRRI dhan104, G13: BRRI dhan107, G14: BINA dhan25, G15: BRRI dhan 88, G16: BRRI dhan81.

2.3. Experimental design and crop management

The field experiment was laid out as a randomized complete block design (RCBD) with three replications, resulting in 48 plots per site. Each plot measured 20 m^2 (4 m × 5 m). For the trial, 300 g of seeds from each genotype were sown in seedbeds, and 35–40-day-old seedlings were manually uprooted and transplanted into the main plots between the second and last week of November 2023. Plant spacing was maintained at 25 cm within rows and 15 cm between rows, with 2–3 seedlings per hill.

Experimental fields were plowed mechanically and prepared following recommended cultivation practices of the Bangladesh Rice Research Institute (BRRI) throughout the growing season (Bangladesh Rice Knowledge Bank, n.d.). Fertilizers were applied at the rate of 138 (300 kg Urea): 20 (100 kg TSP): 83 (165 kg MP): 20 (112 kg Gypsum): 4 (11 kg Zn SO4) kg/ha NPKSZn in the trial. All phosphorus, potassium, sulfur, and zinc were applied during final land preparation, while nitrogen was split into three equal applications at 10, 30, and 40–50 days after transplanting (DAT). Irrigation was applied as needed, and weeds, insects, and other pests were controlled using recommended herbicides, insecticides, and pesticides.

2.4. Assessed traits

Data for the assessed traits were collected at flowering, maturity, and harvest stages. The dates of seeding, transplanting, 50% flowering, and 80% maturity were recorded to calculate the growth duration (GD). Plant height was measured from the soil surface to the tip of the panicle on 10 randomly selected plants per plot, and the values were averaged. The crop was harvested from a 3 m × 3 m area in the center of each plot, excluding border rows, after approximately 80% of the grains had matured. Grain yield (GY) was adjusted to 12% moisture content and converted to tons per hectare (t/ha).

For the estimation of panicle per square meter (PPM), a 1m × 1m area was marked, and the number of panicles was counted within the marking. Ten panicles were randomly selected outside the marking area for GY, and the number of filled and unfilled grains was counted. The average number of filled and unfilled grains was calculated for each panicle. Thousand-grain weight (TGW) was determined in gm by counting and weighing 1000 grains (manually or automatic counting machine). Sterility percentage (STR) was calculated using the formula: STR = (Total unfilled grains / (Total filled grains + Total unfilled grains)) × 100.

2.5. Statistical analyses

Statistical analysis was conducted using Statistics 10 and RStudio console with R version 4.4.1 (R Core Team, 2020). Combined ANOVA analysis and mean separation for genotypes, environments, and genotype-environment interactions (GEI) were performed using Statistics 10. The least significant difference (LSD) test was measured to distinguish mean values at a significance level of $p < 0.05$. Genetic parameters were calculated using the "metan" package in R statistical software. Principal component analysis (PCA) was computed to identify interrelationships among the study traits using the "factoextra" and "FactoMineR" packages in R. Additive main effects and multiplicative interaction (AMMI), Weighted Average of the Absolute Scores biplot (WAASB) and superiority index WAASBY statistical analyses and the Multiple trait stability index (MTSI) analysis were carried out in R software 4.4.1 using the "metan" package (Team, 2020; Olivoto et al. 2019).

AMMI was used to decompose GEIs into principal components, with the analysis performed according to the following equation:

$$yij = \mu + \alpha i + \tau j + \sum_{k=0}^{p} \lambda\ kaiktjk + \rho ij + \varepsilon ij$$

where, y_{ij} is GY response of the i-th genotype in the j-th environment; μ is grand mean; α_i and τ_j represent genotype effect i-th and the environment effect j-th; $\Sigma_{k=0}^{p} \lambda kaiktjk + \rho ij + \varepsilon ij$ is model of multiplicative genotype × environment interaction effect, which λ_k is singular value for the k-th interaction principal component axis (IPCA), a_{ik} is i-th genotype eigenvector for axis k, t_{jk} is the j-th environment eigenvector for axis k; ρ_{ij} stands for the residual not explained by the IPCAs used in the model; and ε_{ij} is error relevant to the model (Olivoto et al., 2019).

The function waasb() computes the Weighted Average of the Absolute Scores considering all possible IPCA from the Singular Value Decomposition of the BLUPs for genotype-vs-environment interaction effects obtained by an Linear Mixed-effect Model (Olivoto et al., 2019), as follows:

$$WAASBi = \sum_{k=1}^{p} | IPCAik \times EPk | \sum_{k=1}^{p} | EPk$$

where WAASBi is the weighted average of absolute scores of the ith genotype; IPCAik is the scores of the ith genotype in the kth IPCA; and EPK is the explained variance of the kth PCA for $k = 1, 2, \ldots, p = \min(g - 1; e - 1)$.

The waasby index is used for genotype ranking considering both the stability (waasb) and mean performance (y) based on the following model (Olivoto, Alessandro D. C. Lúcio, et al., 2019).

$$waasbyi = [(rYi \times \theta Y) + (rWi \times \theta W)] / (\theta Y + \theta W)$$

where waasbyi is the superiority index for the i-th genotype; rYi and rWi are the rescaled values (0-100) for the response variable (y) and the stability (WAAS or WAASB), respectively; θY and θW are the weights for mean performance and stability, respectively.

The third and last step was the estimation of the multi-trait stability index (MTSI), according to Equation (Olivoto et al., 2019):

$$MTSI_i = [\Sigma_{j=1}^{f} (F_{ij} - F_j)^2]^{0.5}$$

where the MTSI is the multi-trait stability index for the ith genotype, Fij is the jth score of the ith genotype, and Fj is the jth score of ideotype. The genotype with the lowest MTSI is then closer to the ideotype and therefore presents a high MPE for all analyzed variables.

3. Results

3.1. Analysis of variance

A combined analysis of variance (ANOVA) was performed for seven agronomic traits of sixteen genotypes evaluated across ten environments during the 2023–24 Boro season (Table 3). The results revealed highly significant variation ($p \leq 0.001$) among replications (R), genotypes (G), environments (E), and genotype × environment interactions (GEI) for all traits. This indicates that genetic, environmental, and their interaction effects significantly influenced grain yield and its related traits.

Table 3

Combine ANOVA of yield and its contributing traits on the basis of mean sum of squares of sixteen genotypes during the Boro 2023-24 season.

Source of variation	df	Mean sum of squares						
		GY	GD	PHT	TGW	PPM	GPP	STR
R	2	0.1035***	1.2***	43.21***	2.1143***	630***	1419.7***	54.222***
G	15	4.67***	328.13***	2295.44***	94.3428***	15944***	8968.3***	818.248***
E	9	24.1025***	1940.71***	1691.7***	36.2097***	111944***	20299.5***	655.815***
GEI	135	1.2359***	53.45***	76.12***	6.3023***	6968***	1508.4***	145.884***
Error	318	0.2038***	0.28***	8.72***	1.0027***	353***	264.6***	26.223***
Total	479							

R: Replication, G: Genotype, E: Environment/ locations, GEI: Genotype-environment interaction, *** significant at 0.1% level of probability, df: Degrees of freedom, GY: Grain yield, GD: Growth duration, PHT: Plant height, TGW: Thousand grain weight, PPM: Panicle per m2, GPP: grains per panicle, STR: sterility percentage. *** indicates significance at $p \leq 0.001$.

3.2. Mean performance of yield and its attributing traits of all rice genotypes

The violin plot (Fig. 3) illustrated the variation in grain yield (GY) across genotypes and environments. Among the sixteen fine-grain rice genotypes, G6 recorded the highest mean GY (7.44 t/ha), followed closely by G9 (7.33 t/ha), G8 (7.27 t/ha), and G7 (7.24 t/ha), which were statistically similar. Growth duration (GD) ranged from 144 days (G15 and G16) to 156 days (G13), while plant height (PHT) varied between 91 cm (G5) and 128 cm (G14). Thousand grain weight (TGW), an indicator of grain size, was highest in G13 (24.98 g), whereas the finest grains were observed in G6 (17.92 g). For other yield-contributing traits, the highest panicle number per m^2 (PPM) was recorded in G4 (342), and the highest grains per panicle (GPP) were observed in G8 (161). Sterility percentage (STR) ranged from 16.88% (G11) to 32.67% (G8). Overall, G6, G7, G8, and G9 combined high grain yield with favorable yield-related traits, indicating their potential for cultivation across diverse environments (Table 4).

Table 4

Mean values of yield and its attributing traits of sixteen fine grain rice genotypes.

Genotypes	GY (t/ha)	GD (days)	PHT (cm)	TGW (g)	PPM	GPP	STR
G1	6.86E	153D	106D	21.46BCD	272GH	124DE	17.06HI
G2	6.49FG	153CD	111B	21.939B	285EF	105G	21.94F
G3	6.02H	149G	106D	21.06DE	276FGH	114FG	17.35HI
G4	7.02CDE	149G	92I	18.84GH	342A	122DE	26.45DE
G5	6.96DE	149G	91I	20.06F	334A	117EF	26.21DE
G6	7.44A	148H	97G	17.92I	323B	139C	29.48BC
G7	7.24ABC	149G	99F	19.01G	322B	151B	28.34CD
G8	7.27AB	150F	99F	18.56GH	322B	161A	32.67A
G9	7.33AB	149F	99F	18.40HI	311C	150B	32.01AB
G10	6.48FG	150E	102E	21.08DE	310C	112FG	19.21GHI
G11	6.38G	154B	108C	20.60E	298D	128D	16.88I
G12	6.93DE	154B	99F	21.70BC	317BC	106G	21.59FG
G13	7.11BCD	156A	105D	24.98A	293DE	110FG	21.27FG
G14	6.61F	153C	128A	21.02DE	268H	142C	25.62E
G15	6.99DE	144I	95H	21.31CD	310 C	115EF	19.53FGH
G16	6.57FG	144I	98F	21.64BC	278FG	127D	21.36FG
CV%	6.58	0.35	2.89	4.86	6.18	12.85	21.74
$LSD_{0.05}$	0.23	0.27	1.5	0.51	9.54	8.26	2.6

LSD: Least significant differences among mean values at 5% level of significant, CV: Coefficient of variations, G1: BR10645-6-4-8-1-2, G2: BR10646-3-2-2-4-3, G3: BR10648-12-1-3-4-1, G4: BRH15-24-7B, G5: BR9392-1-7-5B, G6: BR17-23-8-2-7B, G7: BRH11-7-17-10B, G8: BRH9-3-2B, G9: BRH13-9-5-2B, G10: Zira, Nachol, G11: Katari, Shibganj, G12: BRRI dhan104, G13: BRRI dhan107, G14: BINA dhan25, G15: BRRI dhan 88, G16: BRRI dhan81, GY: Grain yield, GD: Growth duration, PHT: Plant height, TGW: Thousand grain weight, PPM: Panicle per m2, GPP: grains per panicle, STR: sterility percentage.

On the other hand, Table 5 exhibits the mean values of eight yield and yield-contributing traits across ten different locations during the Boro 2023-24 growing season. Fig. 3 displayed that the highest GY was recorded in E3 (Bhanga, Faridpur) at 8.29 t/ha. The second highest grain yield was found 7.49 t/ha in both E7 (Mithapukur, Rangpur) and E10 (West byde, BRRI, Gazipur) environments. The poorest performance was observed in E5 (5.81 t/ha) followed by E2 (6.20 t/ha) and E8 (6.14 t/ha) in terms of grain yield. The similar result also observed for growth duration. These two environments E2 and E8 also displayed the lowest growth duration 143 days and 144 days, respectively. While, the longest growth duration was recorded in E4 (162 days) followed by E7 (157 days). The tallest PHT was observed in E1 (Paba, Rajshahi) at 112 cm, whereas E9 (Kamarkhanda, Sirajganj) recorded the shortest at 87.61 cm. In case of TGW, E4 (Kamarkhanda, Sirajganj) had the highest value at 21.67 g which was statistically similar to 21.49 g found at E5 (Sadar, Satkhira). The lowest TGW was observed in E1 region. E3 showed the highest PPM at 381, whereas E2 had the lowest at 264. E7 region had the highest GPP at 159 and the minimum result was found in E4 region. Furthermore, the highest STR was recorded in E1 at 30.86%, while E4 had the lowest at 19.17%.

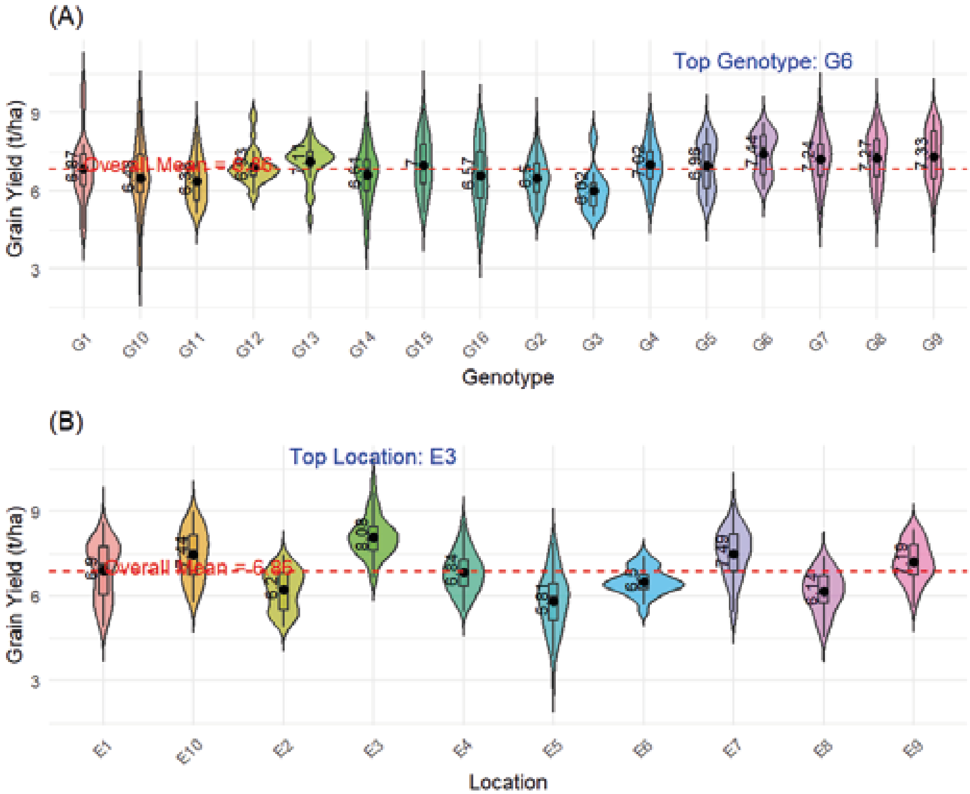

Fig. 3. Violin plots of mean grain yield results (A) Mean grain yield (t/ha) of the genotypes (B) Mean grain yield (t/ha) of all locations. G1: BR10645-6-4-8-1-2, G2: BR10646-3-2-2-4-3, G3: BR10648-12-1-3-4-1, G4: BRH15-24-7B, G5: BR9392-1-7-5B, G6: BR17-23-8-2-7B, G7: BRH11-7-17-10B, G8: BRH9-3-2B, G9: BRH13-9-5-2B, G10: Zira, Nachol, G11: Katari, Shibganj, G12: BRRI dhan104, G13: BRRI dhan107, G14: BINA dhan25, G15: BRRI dhan 88, G16: BRRI dhan81, E1: Paba, Rajshahi, E2: Sadar, Kushtia, E3: Bhanga, Faridpur, E4: Kamarkhanda, Sirajganj, E5: Sadar, Satkhira, E6: Debidwar, Cumilla, E7: Mithapukur, Rangpur, E8: Sonagazi, Feni, E9: Sadar, Gopalganj, E10: BRRI Westbyde, Gazipur.

Table 5
Locational mean values of yield and yield attributing traits of PQR genotypes during Boro 2023-24 season.

Environments	GY (t/ha)	GD (days)	PHT (cm)	TGW (g)	PPM	GPP	STR
E1	6.89D	149F	112A	19.56EF	283E	146B	30.86A
E2	6.20F	143J	103F	20.17CD	264F	115E	22.70DE
E3	8.08A	153D	107B	19.20F	381A	141BC	28.29B
E4	6.84D	162A	106C	21.67A	315C	101F	19.17F
E5	5.81G	152E	97H	21.49A	313C	128D	23.28CD
E6	6.50E	145H	95I	20.51C	217G	119E	20.73EF
E7	7.49B	157B	105D	21.27AB	276E	159A	22.36DE
E8	6.14F	144I	102G	21.28AB	315C	92G	25.19C
E9	7.19C	146G	92J	20.99B	371B	137C	19.70F
E10	7.44B	155C	104E	19.85DE	302D	128D	23.32CD
$LSD_{0.05}$	0.18	0.21	1.19	0.4	7.55	6.53	2.06

LSD: least significant differences among mean values at 5% level of significant, E1: Paba, Rajshahi, E2: Sadar, Kushtia, E3: Bhanga, Faridpur, E4: Kamarkhanda, Sirajganj, E5: Sadar, Satkhira, E6: Debidwar, Cumilla, E7: Mithapukur, Rangpur, E8: Sonagazi, Feni, E9: Sadar, Gopalganj, E10: BRRI Westbyde, Gazipur. GY: Grain yield, GD: Growth duration, PHT: Plant height, TGW: Thousand grain weight, PPM: Panicle per m2, GPP: grains per panicle, STR: sterility percentage.

3.3. Genetic parameters of studied traits

Genetic parameters for seven yield and yield-contributing traits of sixteen fine-grain rice genotypes across ten environments were estimated using a linear mixed model (Table 6). The phenotypic variance (σ^2_p) was highest for panicle number per m^2 (PPM, 2854), followed by grains per panicle (GPP, 927), indicating substantial variation among genotypes for these traits. Broad-sense heritability (h^2b), which estimates the proportion of total phenotypic variance attributable to genetic factors, ranged from 0.11 (PPM) to 0.71 (plant height), while mean-based heritability (h^2mg), calculated across environments, was higher, ranging from 0.56 to 0.97, reflecting strong genetic control for most traits.

The coefficient of determination of genotype × environment interaction effects (GEI r^2) varied between 0.22 and 0.77, suggesting that some traits were more influenced by environmental interactions than others. Selection accuracy (SA) was generally high (>0.80) for all traits, except PPM (0.75), indicating reliable genotype selection. Genotype–environment correlation (rge) was strongest for growth duration (GD, 0.99) and PPM (0.86), while grain yield (GY) showed moderate correlation (0.62), highlighting the influence of environment on yield. The ratio of genotypic to residual coefficient of variation (CVg / CVr) ranged from 0.74 to 5.75, with the highest value observed for GD, indicating that genotypic variation was relatively greater than residual variation for certain traits.

Overall, the analysis indicates that traits such as plant height, thousand-grain weight (TGW), and GD are largely under genetic control, while traits like PPM and GPP are more affected by environmental interactions, providing useful insights for selection in multi-environment trials.

Table 6
Genetic parameters of yield and its attributing traits of sixteen fine grain rice genotypes studied under 10 locations in LMM.

Parameters	GY	GD	PHT	TGW	PPM	GPP	STR
σ^2_p (%)	0.665	27.2	105	5.72	2854	927	87.9
h^2_b	0.17	0.34	0.71	0.51	0.11	0.27	0.26
GEIr2	0.52	0.65	0.22	0.31	0.77	0.45	0.46
h^2_{mg}	0.74	0.84	0.97	0.93	0.56	0.83	0.82
SA	0.86	0.92	0.98	0.97	0.75	0.91	0.91
r_{ge}	0.62	0.99	0.73	0.63	0.86	0.62	0.61
CV_g	4.93	2.01	8.41	8.32	5.69	12.5	20.1
CV_r	6.65	0.349	2.83	4.91	6.14	12.8	21.4
CV ratio	0.74	5.75	2.97	1.69	0.93	0.98	0.94

σ2p: Phenotypic variance, h2b: Broad sense heritability, GEIr2: Coefficient of determination of the interaction effects, h^2_{mg}: Mean basis heritability, SA: Selection accuracy, r_{ge}: Genotype-environment correlation, CVg: genotypic coefficient of variation, CVr: residual coefficient of variation, CV ratio: ratio of CV_g and CV_r, GY: Grain yield, GD: Growth duration, PHT: Plant height, TGW: Thousand grain weight, PPM: Panicle per m^2, GPP: grains per panicle, STR: sterility percentage.

3.4. Principal component analysis (PCA)

Principal component analysis (PCA) was conducted to explore patterns of variation and relationships among seven yield and yield-contributing traits by reducing data dimensionality. Seven principal components (Dim-1 to Dim-7) were initially identified, with Dim-1 and Dim-2 explaining the majority of the variance (49.1%; Fig. 4), indicating that two components capture nearly half of the variability among genotypes. In the PCA biplot, traits located close to each other reflect positive correlations, whereas traits positioned in opposite directions indicate negative correlations.

Dim-1 was primarily influenced by grain yield (GY), grains per panicle (GPP), panicles per m^2 (PPM), thousand grain weight (TGW), and sterility percentage (STR). The positive association of GY with PPM and GPP suggests that genotypes with more panicles and higher grain number per panicle tend to produce higher yields. Conversely, the negative correlation between GY and TGW indicates a trade-off between grain size and overall yield under the tested environments. Dim-2 was mainly associated with plant height (PHT) and growth duration (GD), reflecting differences in vegetative growth patterns and maturity among genotypes. Genotypes with taller plants and longer growth duration tend to have different resource allocation strategies compared to early-maturing or shorter genotypes.

The color gradient in the biplot highlights trait contributions, with red representing the highest contribution (GD) and blue the lowest (PPM), further emphasizing that growth duration strongly differentiates genotypes along Dim-2, while yield components largely drive variation along Dim-1. These results indicate that selection for high-yielding genotypes should consider both panicle and grain number, while accounting for the negative association with grain size. Similarly, genotypes with favorable combinations of plant height and growth duration can be targeted for adaptation to specific environments.

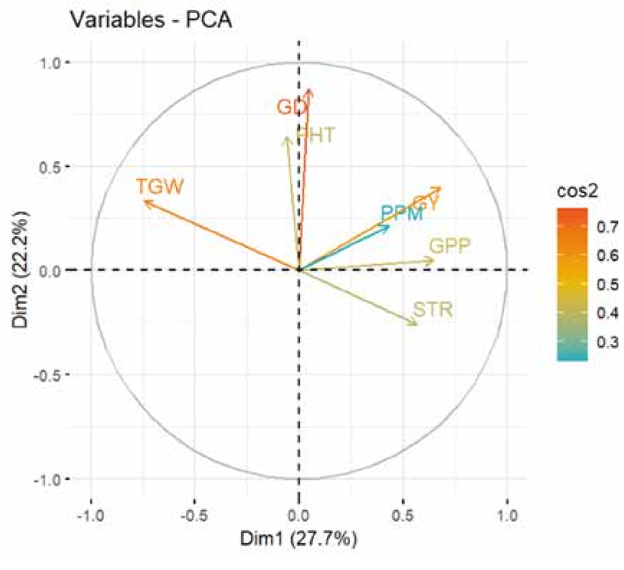

Fig. 4. Principal component analysis of yield and its attributing traits for Dim1 and Dim2.

3.5. Mean yield performance for GEI

Fig. 5 illustrates the GEI effects on GY using heatmap. The columns and rows represent the genotypes and environments, respectively. The color gradient ranging from purple to yellow indicating the lower to higher grain yield. Variability in GY is evident across E and G, with significant differences observed in mean yield values. The highest GY was recorded in the E3 region for the G1 genotype, reaching 9.7 t/ha, followed by G7 at 8.7 t/ha in E7 region and G15 at 8.7 t/ha in E3 region. Conversely, the lowest yield was observed in G10, measuring 3.9 t/ha in the E5 region followed by G16 and G14 with 4.5 t/ha in the same environment.

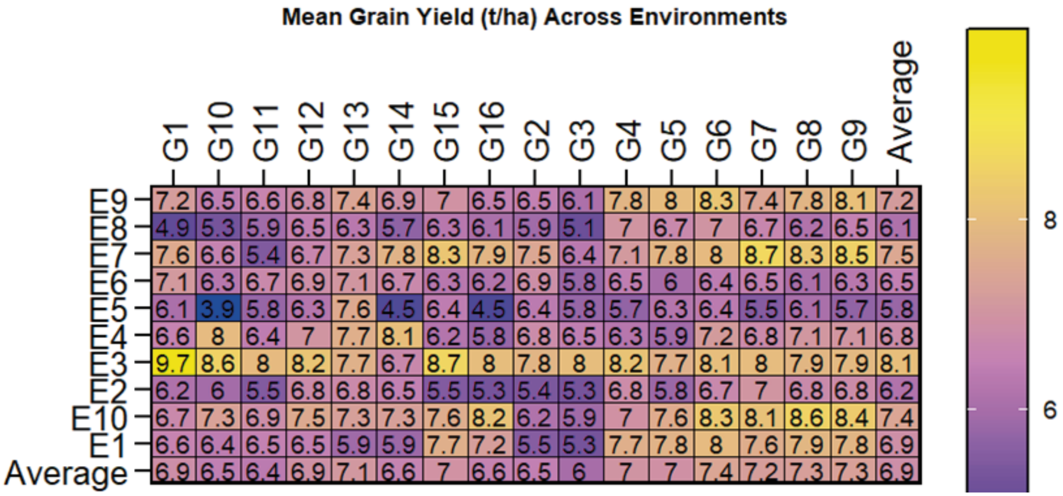

Fig. 5. The mean performance of grain yield (t/ha) of studied sixteen (16) rice genotypes across ten (10) environments during the 2023-24 Boro season. G1: BR10645-6-4-8-1-2, G2: BR10646-3-2-2-4-3, G3: BR10648-12-1-3-4-1, G4: BRH15-24-7B, G5: BR9392-1-7-5B, G6: BR17-23-8-2-7B, G7: BRH11-7-17-10B, G8: BRH9-3-2B, G9: BRH13-9-5-2B, G10: Zira, Nachol, G11: Katari, Shibganj, G12: BRRI dhan104, G13: BRRI dhan107, G14: BINA dhan25, G15: BRRI dhan 88, G16: BRRI dhan81, E1: Paba, Rajshahi, E2: Sadar, Kushtia, E3: Bhanga, Faridpur, E4: Kamarkhanda, Sirajganj, E5: Sadar, Satkhira, E6: Debidwar, Cumilla, E7: Mithapukur, Rangpur, E8: Sonagazi, Feni, E9: Sadar, Gopalganj, E10: BRRI Westbyde, Gazipur.

3.6. AMMI analysis of variance

Table 7 presents the AMMI ANOVA, highlighting the contributions of different sources of variation to the total sum of squares (TSS) observed in the selected genotypes dataset for GY. The analysis of variance revealed that GY was significantly affected by E, G and GEI, with a p-value less than 0.001. The majority of the total sum of squares (TSS) in the model was attributed to E (216.98), followed by GEI (166.89) and G (70.01). The interaction of the first two principal components (PCs) accounted for approximately 61% of the variance. Among the PCs of the AMMI ANOVA, the first six PCs were significant at ≤0.01 probability, contributing to a total of 95.9% of the variance.

Table 7
AMMI analysis of variance of rice grain yield (GY) (t/ha) for sixteen rice genotypes studied under 10 locations during 2023-24 Boro season.

Source	Df	TSS	MSS	Proportion	Accumulated
E	9	216.98	24.11***	-	-
R (E)	20	2.69	0.13	-	-
G	15	70.01	4.67***	-	-
GEI	135	166.89	1.24***	-	-
PC1	23	63.03	2.74***	37.8	37.8
PC2	21	38.69	1.84***	23.2	61.0
PC3	19	26.87	1.41***	16.1	77.1
PC4	17	17.64	1.04***	10.6	87.6
PC5	15	7.67	0.51**	4.6	92.2
PC6	13	6.16	0.47**	3.7	95.9
PC7	11	3.70	0.34	2.2	98.1
PC8	9	2.43	0.27	1.5	99.6
PC9	7	0.69	0.10	0.4	100
Residuals	300	62.34	0.21	-	-
Total	614	685.79	1.12	-	-

E: Environment/ location, R: Replication, G: Genotype, GEI: Genotype-environment interaction, *** significant at 0.001% level of probability, ** significant at 0.01% level of probability, df: Degrees of freedom, TSS: Total sum of square, MSS: Mean sum of square, PC: Principal component.

3.7. Additive main effects and multiplicative interaction (AMMI1 & AMMI2) biplot

Additive main effects and multiplicative interaction 1 (AMMI 1) depicts the biplot abscissa and ordinate illustrating the first principal component analysis (PCA1) and main effects of Grain yield (GY) (Figure 6). The first PCA scores were plotted against the second PCA scores to generate the biplot for the environments and genotypes when compared (Figure 6). The AMMI 2 revealed the importance of PCA2 scores along the first PCA in explaining the complexity of GEI involving significant multi-environments and identifying the adaptation of genotypes. The 16 accessions tested in the ten environments allowed us to understand the GEI using AMMI through the trait of GY. Similarities and dissimilarities among the 16 accessions were observed on the basis of the GEI study. In this study, the PCA values interactions accounted for 61% of the G + G × E interaction variation for the GY, shown in the AMMI2 biplot. The genotypes were closer to origin indicating zero scores; at the same time, those placed at the right side of the center of the axis had higher performance than the accessions found at the left-hand side. It appears that genotypes G4, G14 were closer to the origin in AMMI1 biplot, but genotypes G3, G9, G13, and G16 were far from the origin. In Figure 5, G6, G7, G8, G9, G12 and G13 located on the right side of the center of the axis had higher yields than G2, G3, G10, G11 and G16. On the other hand, in AMMI 2 biplot, G12 was close to the origin, while G5, G8, G13 and G14 were far from the center. Environment E3, E6 and E7 had practically low contribution on the first PCA1, while E4, E5 and E10 had a high score on the first and second PCAs for grain yield. For grain yield, it was observed that genotypes G8 and Environments E7 and E10 had a significant effect on the GE interaction.

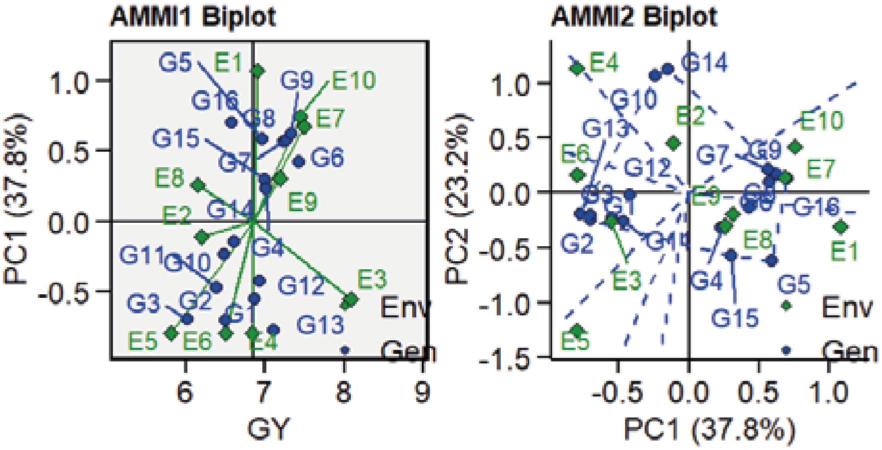

Fig. 6. Additive main effects and multiplicative interaction (AMMI) 1 & 2 biplots based on PC1 and PC2 illustrating G × E interactions of the 16 fine grain rice accessions under ten sites for GY. PC1: Principal Component 1, PC2: Principal Component 2.

3.8. Genotype Stability and Ranking Based on WAASB and WAASBY

In this study, the stability and performance of 16 rice genotypes across ten environments for the 2023–24 Boro seasons were also evaluated using Weighted Average of Absolute Scores from BLUPs (WAASB) and Weighted Average of Absolute Scores from the BLUPs and Yield (WAASBY) indices (Table 8). The WAASB index measures stability, with lower values indicating greater stability. While the WAASBY index combines both yield and stability, where higher values are preferable. The WAASB biplots and WAASBY graphs (Fig. 7) illustrate the stability and performance of the selected genotypes across environments.

In the WAAS biplot, all entries were divided into four quadrants. The quadrant I considered unstable genotypes or environments with high discrimination ability, and with productivity below the grand mean. The second quadrant (II) consists of unstable but highly productive genotypes. Genotypes within quadrant III have low productivity, but can be considered stable due to the lower values of WAASB.

The genotypes within the quadrant IV are highly productive and broadly adapted due to the high magnitude of the response variable and high stability performance (lower values of WAASB). Genotypes G6, G4, G9, G8, G7, and G12 were positioned in Quadrant IV, indicating high discriminative ability and high representativeness, with WAASB values ranging between 0.24 and 0.32 (Table 8). Among them, G12 had the lowest WAASB value. Conversely, the highest WAASB score (0.47) was found for G10, which was positioned in Quadrant I along with G2 and G14, indicating poor and unstable performance. However, G13 displayed a high WAASB value (0.46), second only to G10, suggesting instability despite its high yield. Furthermore, G3 and G11 showed low discriminating ability across locations and were positioned in Quadrant III.

The WAASBY plot (Fig. 7) ranked genotypes based on combined yield and stability, categorizing them as above-average (blue) or below-average (red) performers. From the figure 7B, it observed that 7 out of 16 genotypes performed above average. G6 ranked highest (WAASBY = 91.45), followed by G12, G4, G8, G9, and G7 (WAASBY ~80), demonstrating a strong balance of high yield and stability. In contrast, 9 genotypes fell below average, indicated lower suitability for broad adaptation. Genotypes G10 followed by G3, G2 remained lowest position in the below average in WAASBY rankings.

Table 8

Mean grain yield (t/ha), WAASB and WAASBY scores of genotypes under study: rRESP – genotype ranking based on grain yield, rWAASB – genotype ranking based WAASB, rWAASBY – genotype ranking based WAASBY.

Genotype	Mean grain yield (t/ha)	rResp	WAASB	rWAASB	WAASBY	rWAASBY
G1	6.87	10	0.44	14	35.02	11
G10	6.48	14	0.47	16	16.10	16
G11	6.38	15	0.36	9	35.94	10
G12	6.93	9	0.24	1	82.21	2
G13	7.11	5	0.46	15	40.88	9
G14	6.61	11	0.42	13	30.73	13
G15	7.00	7	0.34	7	61.14	7
G16	6.57	12	0.41	11	32.51	12
G2	6.50	13	0.41	12	28.49	14
G3	6.02	16	0.35	8	25.71	15
G4	7.02	6	0.26	2	80.64	3
G5	6.96	8	0.38	10	52.40	8
G6	7.44	1	0.28	3	91.45	1
G7	7.24	4	0.31	5	77.59	6
G8	7.27	3	0.30	4	80.32	4
G9	7.33	2	0.32	6	79.13	5

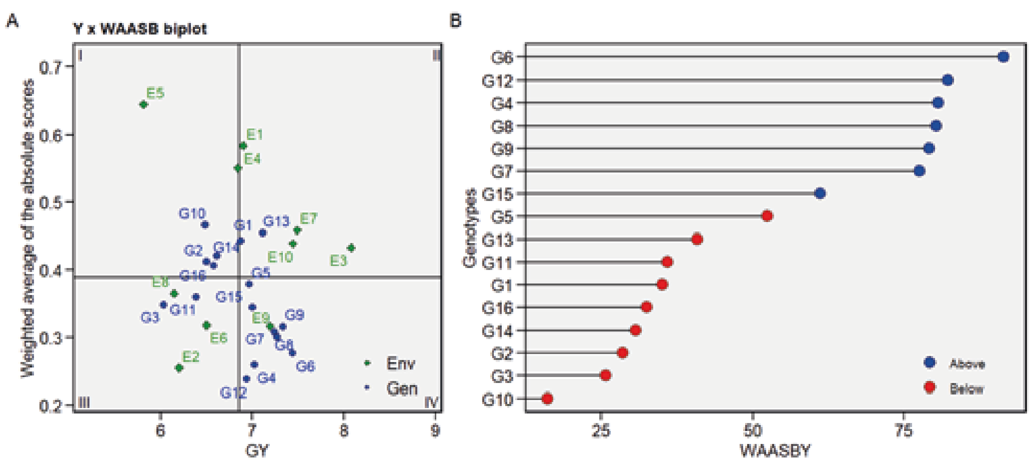

Fig. 7. WAASB statistic. A) Biplot of the mean grain yield and B) the weighted average of absolute scores for the best linear unbiased predictions of the genotype-vs.-environment interaction during 2023-24 season. WAASB: Weighted Average of Absolute Scores Biplot, WAASBY: Weighted Average of Absolute Scores Yield, G1: BR10645-6-4-8-1-2, G2: BR10646-3-2-2-4-3, G3: BR10648-12-1-3-4-1, G4: BRH15-24-7B, G5: BR9392-1-7-5B, G6: BR17-23-8-2-7B, G7: BRH11-7-17-10B, G8: BRH9-3-2B, G9: BRH13-9-5-2B, G10: Zira, Nachol, G11: Katari, Shibganj, G12: BRRI dhan104, G13: BRRI dhan107, G14: BINA dhan25, G15: BRRI dhan 88, G16: BRRI dhan81, E1: Paba, Rajshahi, E2: Sadar, Kushtia, E3: Bhanga, Faridpur, E4: Kamarkhanda, Sirajganj, E5: Sadar, Satkhira, E6: Debidwar, Cumilla, E7: Mithapukur, Rangpur, E8: Sonagazi, Feni, E9: Sadar, Gopalganj, E10: BRRI Westbyde, Gazipur.

3.9. Multitrait stability index (MTSI)

Table 9 displays the results of the factor analysis, which reveal the selection gain percentage (SG) (%), desired selection sense, and the achievement status of the goal based on factor analysis of selected rice genotypes using seven traits. The factor analysis revealed that contributing factors formed into three distinct groups consisting of eight traits under study. The desired selection sense was to increase for all traits. The goal was successfully achieved for four traits (GY, PPM, GPP and STR). The goal of 3 traits such as PHT, GD and TGW was 0 as well as negative SG (%). Furthermore, the SG (%) for studied traits was ranged from 5.76 to 29.5%. The Fig. 8 illustrated the order of the most stable genotype determined by the multi-trait stability indexing (MTSI). Within this context, the red circle symbolizes the threshold for selecting the stable genotype. The genotype named G7 and G8 stands out as the most stable compared to other genotypes.

Table 9
Factor analysis of seven traits in sixteen fine grain rice genotypes for MTSI.

VAR	Factor	X_o	X_s	SD	SG (%)	Sense	Goal
GY	FA1	6.86	7.25	0.395	5.76	increase	100
PPM	FA1	304	322	18.6	6.12	increase	100
STR	FA1	23.6	30.5	6.95	29.5	increase	100
PHT	FA2	102	99.3	-2.97	-2.9	increase	0
GD	FA3	151	150	-1.04	-0.687	increase	0
TGW	FA3	20.6	18.8	-1.81	-8.8	increase	0
GPP	FA3	127	156	29.4	23.2	increase	100

Xo: Observed mean, Xs: Mean of selected genotypes, SG: Selection gain, FA: factor, GY: Grain yield, GD: Growth duration, PHT: Plant height, TGW: Thousand grain weight, PPM: Panicle per m2, GPP: grains per panicle, STR: sterility percentage.

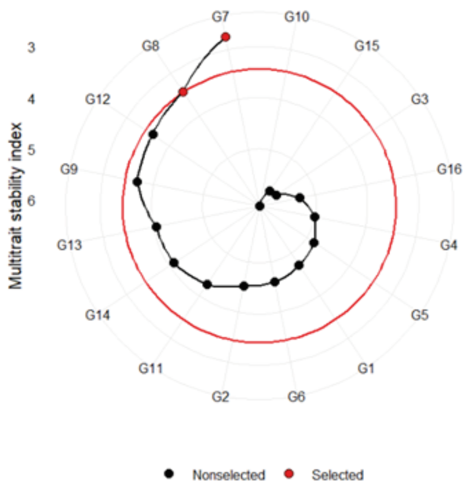

Fig. 8. Ranking of genotype stability based on MTSI index. MTSI: Multitrait stability index.

4. Discussion

This study aimed to evaluate the yield stability of 16 fine grain rice genotypes across ten diverse agro-ecological zones in Bangladesh. By conducting a comprehensive analysis of variance (ANOVA) for grain yield and its contributing traits, we observed significant effects of genotype, environment, and genotype-environment interaction (GEI), aligning with previous research findings (Akter et al., 2016; Huang et al., 2021). The detected profound differences among genotypes and environments can largely be attributed to variations in environmental conditions, the genetic diversity inherent in the studied genotypes, and the complex interactions between these two variables.

To select ideal genotypes for commercial application, it is essential for plant breeders to assess genetic parameters and stability of key traits. This study employed broad-sense heritability (h^2), coefficients of variation (CV), and selection accuracy (SA) to explore the genetic diversity among the genotypes (Dyulgerova and Dyulgerov 2024; Fellahi et al., 2020; Resende and Alves 2022). Our findings confirm that phenotypic variance exhibited sensitivity to environmental factors, with the GEI exerting the dominant influence on phenotypic variance in grain yield. This interaction resulted in lower heritability estimates, which ranged from 11% to 71% (Table 6), consistent with earlier observations (Dyulgerova and Dyulgerov 2024). An SA above 50% indicates this was acceptable for verifying the significance of genetic effects in the context of the heritability of the trait (h^2), genotypic correlation across environments ($r_{(e)}$), and the number of repetitions in multi-environment trials (Resende & Alves, 2022).

This analysis revealed high genetic diversity among genotypes, demonstrated by CV ratios, particularly for growth duration (GD), plant height (PHT), and thousand grain weight (TGW), all exceeding 1. The implications of this genetic diversity suggest a potential for selective breeding to enhance yield. However, variance component analysis alone cannot fully elucidate the complexities of GEI. Employing more advanced statistical models would be advantageous in providing deeper insights into the GEI (Mukul et al., 2025; Oladosu et al., 2017).

Through principal component analysis (PCA), GD and GY emerged as the most significant traits contributing to the overall agronomic performance, reinforcing the insight from previous studies (Chandra et al., 2021; Oladosu et al., 2018). These findings resonate with considerations of rice growth stage dynamics—an extended growth duration typically correlates with increased yields while plant height is also a crucial parameter (Biswash et al., 2023; Limbongan et al., 2024; Shrestha et al., 2021; Zhu et al., 2023; Ahmed et al., 2017; Chen et al., 2022; Shrestha et al., 2021). Interestingly, certain high-yield cultivars demonstrated optimal yield within shorter growth periods, suggesting that specific gene expressions may enhance yield performance regardless of growing time (Wei et al., 2022).

Utilizing the additive main effects and multiplicative interaction (AMMI) model allowed for a more nuanced identification of superior lines compared to check varieties, offering enhanced accuracy over traditional ANOVA methods (Gauch and Zobel 1997). The results (Table 8) suggest that the first two PCs accounted for 61% of the variance, in alignment with previous work advocating for the use of fewer PCs in multi-environment trials (Mukul et al., 2025; Ahmed, 2025; Esan et al., 2023; Gauch and Zobel 1996). In the AMMI biplot, genotypes G6, G7, G8, and G9 exhibited the best yield performance, indicating their potential for broader adaptability.

Since breeders always prefer the yield performance with stability for varietal recommendations, so a mixed-effect model-based superiority index, WAASBY helps to identify the adaptability and productivity combining weighting between performance of response variable and WAASB stability score. The WAASB statistics were calculated based on mean GY and stability, integrating AMMI analysis and the BLUP model to examine the GEI effect (Olivoto et al., 2019). WAASB stability index has been employed in identification of stable genotypes in different economic traits such grain yield in rice (Hasan et al., 2025; Mukul et al., 2025; Hossain et al., 2023), grain yield in maize (Supriadi et al., 2024), yield performance of wheat (Al-Ashkar et al., 2023), grain yield in soyabean (Nataraj et al., 2021) and forage sorghum (Behera et al., 2024). In this study, G6 identified as the most outstanding genotype, combining the highest mean grain yield (7.44 t/ha) with strong stability (WAASB = 0.28), resulting in the highest WAASBY score (91.45). Similarly, G12, although slightly lower in yield (6.93 t/ha), demonstrated exceptional stability (WAASB = 0.24), leading to the second-highest WAASBY value (82.21). Genotypes G4, G8, and G9 also exhibited favorable combinations of high yield and moderate to high stability, ranking among the top five based on the WAASBY index. In contrast, G10, G3, and G2 showed poor performance in both yield and stability, making them less suitable for recommendation. The GY × WAASB biplot supported these findings by clearly positioning superior genotypes like G6 and G8 in the desirable quadrant of high yield and low instability.

Lastly, our findings reveal that the overall reliability of genotype recommendations significantly increases by taking into account both yield performance and stability across multiple traits. The positive correlation of yield efficiency with associated traits during growth further underscores the complexity of breeding decisions (Fageria, 2007). This study advocates for the implementation of multi-trait selection indices (MTSI) to enhance genotype evaluation. Key performers G7 and G8 excelled in all seven assessed traits, echoing the approaches previously adopted by researchers for comprehensive genotype assessments (Hasan et al., 2025; Habib et al., 2024; Lee et al., 2023; Olivoto et al., 2019; Sruthi et al., 2024).

5. Conclusion

In conclusion, statistical approaches such as the AMMI and WAASB biplot revealed that four advanced genotypes (G6, G7, G8, and G9) demonstrated superior performance and adaptability across varied environments compared to the released check varieties. Additionally, the integration of multi-trait selection indices (MTSI) confirmed G7 and G8 as top performers across multiple traits, highlighting the importance of incorporating stability and multi-trait assessments into breeding programs. These findings will accelerate the development of climate-resilient rice varieties in Bangladesh, particularly focusing on the superior yield performance and stability of genotypes Future investigations should evaluate these promising genotypes under specific stress-prone conditions, such as heat and drought during the reproductive stage, as well as in lowland and rainfed agro-ecological zones where environmental variability is highest. Such targeted trials, combined with advanced statistical approaches, will refine genotype recommendations and support the development of high-yielding, stress-resilient rice varieties suitable for Bangladesh's diverse rice-growing regions.

Conflict of Interest

"The authors declare no conflict of interest."

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References

Ahmed, K. K. (2025). Performance and stability of premium quality rice varieties in multi-environment trials using AMMI and GGE biplot during the Boro season in Bangladesh. International Journal of Natural and Social Sciences, 12(1), 01–12. https://doi.org/10.5281/zenodo.14728939

Ahmed, M., Haq, M.E., Hossain, M.M., Shefat-al-Maruf, M., & Hasan, M.M. (2017). Performance of Four Different Rice Cultivars under Drought Stress in the North-Western Part of Bangladesh. International Journal of Agriculture and Forestry, 2017, 134-139.

Akter, A., Hasan, Md. J., Kulsum, U., Rahman, M., Paul, A., Lipi, L., & Akter, S. (2016). Genotype × Environment Interaction and Yield Stability Analysis in Hybrid Rice (*Oryza sativa* L.) By AMMI Biplot. Bangladesh Rice Journal, 19, 79. https://doi.org/10.3329/brj.v19i2.28168

Alam, M., Lou, G., Abbas, W., Osti, R., Ahmad, A., Bista, S., Ahiakpa, J. K., & He, Y. (2024). Improving Rice Grain Quality Through Ecotype Breeding for Enhancing Food and Nutritional Security in Asia–Pacific Region. Rice, 17(1), 47. https://doi.org/10.1186/s12284-024-00725-9

Al-Ashkar, I., Sallam, M., Almutairi, K. F., Shady, M., Ibrahim, A., & Alghamdi, S. S. (2023). Detection of High-Performance Wheat Genotypes and Genetic Stability to Determine Complex Interplay between Genotypes and Environments. Agronomy, 13(2), Article 2. https://doi.org/10.3390/agronomy13020585

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

Behera, P. P., Singode, A., Bhat, B. V., Ronda, V., Borah, N., Yue, H., Verma, H., Borah, J. L., Majhi, P. K., Saharia, N., Gogoi, L. R., & Sarma, R. N. (2024). WAASB-based stability analysis and simultaneous selection of forage sorghum for forage yield traits. Euphytica, 220(9), 145. https://doi.org/10.1007/s10681-024-03397-0

Biswash, M., Kabir, H., Morshed, M., Khatun, M., Ahmed, K., Mir Hossain, M., Hasan, M. M., Zahan, A., Shamsunnaher, F., Islam, R., & Islam, A. (2023). Adaptation of some cold tolerant Rice genotypes in Haor areas of Bangladesh. International Journal of Biosciences (IJB), 22, 33–40. https://doi.org/10.12692/ijb/22.2.33-40

Chandra, B. S., Reddy, T. D., Ansari, N. A., & Kumar, S. S. (2009). Correlation and path analysis for yield and yield components in rice (*Oryza sativa* L.). Agricultural Science Digest, 29(1), 45-47.

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), Article 8. https://doi.org/10.3390/agronomy12081739

Custodio, M. C., Cuevas, R. P., Ynion, J., Laborte, A. G., Velasco, M. L., & Demont, M. (2019). Rice quality: How is it defined by consumers, industry, food scientists, and geneticists? Trends in Food Science & Technology, 92, 122–137. https://doi.org/10.1016/j.tifs.2019.07.039

Custodio, M. C., Demont, M., Laborte, A., & Ynion, J. (2016). Improving food security in Asia through consumer-focused rice breeding. Global Food Security, 9, 19–28. https://doi.org/10.1016/j.gfs.2016.05.005

Dyulgerova, B., & Dyulgerov, N. (2024). Genotype-by-year interaction and simultaneous selection for grain yield and stability in winter barley. Bulgarian Journal of Agricultural Science, 30(3).

Esan, V. I., Oke, G. O., Ogunbode, T. O., & Obisesan, I. A. (2023). AMMI and GGE biplot analyses of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] for agronomic performances under three environmental conditions. Frontiers in Plant Science, 13. https://doi.org/10.3389/fpls.2022.997429

Fageria, N. K. (2007). Yield Physiology of Rice. Journal of Plant Nutrition, 30(6), 843–879. https://doi.org/10.1080/15226510701374831

Fellahi, Z. E. A., Hannachi, A., & Bouzerzour, H. (2020). Expected genetic gains from mono trait and index- based selection in advanced bread wheat (*Triticum aestivum* L.) populations. Revista Facultad Nacional de Agronomía Medellín, 73, 9131–9141. https://doi.org/10.15446/rfnam.v73n2.77806

Gauch, Hugh. G., & Zobel, R. W. (1997). Identifying Mega-Environments and Targeting Genotypes. Crop Science, 37(2), 311–326. https://doi.org/10.2135/cropsci1997.0011183X003700020002x

Gauch, J. (1992). Statistical analysis of regional yield trials: AMMI analysis of factorial designs. https://www.cabidigitallibrary.org/doi/full/10.5555/19931643324

Gauch R., H., & Zobel, W. (1996). AMMI Analysis of Yield Trials. In H. G. Gauch & M. Kang (Eds.), Genotype-by-Environment Interaction (pp. 85–122). CRC Press. https://doi.org/10.1201/9781420049374.ch4

Habib, M. A., Azam, M. G., Haque, M. A., Hassan, L., Khatun, M. S., Nayak, S., Abdullah, H. M., Ullah, R., Ali, E. A., Hossain, N., Ercisli, 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. https://doi.org/10.1038/s41598-024-64808-9

Hasan, M. M., Alam, Z., Mukul, M. H. R., Zahan, A., Morshed , M. N., Ahmed , K. K., Bishwas , M. R., Gaffar, M. A., Badhan, A., Akter , S., Karmakar , B., & Kabir, M. H. (2025). Selection of Stable and High-Yielding Short-Duration Inbred Rice (*Oryza sativa* L.) Genotypes for the Boro Season in Bangladesh Using WAASB and MTSI Indices. IV. International Congress of the Turkish Journal of Agriculture - Food Science and Technology, Niğde, Türkiye, 901–914. gönderen https://www.turjaf.com/index.php/TURSTEP/article/view/582

Hossain, M. A., Mamun, M. A. A., Rabbi, S. M. H. A., Akter, S., & Roy, R. K. (2023). Selection of Stable Rice Genotypes through WAASB and MTSI Indices. Current applied science and technology, e0263298–e0263298. https://doi.org/10.55003/cast.2025.263298

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), Article 6. https://doi.org/10.3390/agriculture11060558

Lee, S. Y., Lee, H.-S., Lee, C.-M., Ha, S.-K., Park, H.-M., Lee, S.-M., Kwon, Y., Jeung, J.-U., & Mo, Y. (2023). Multi-Environment Trials and Stability Analysis for Yield-Related Traits of Commercial Rice Cultivars. Agriculture, 13(2), Article 2. https://doi.org/10.3390/agriculture13020256

Limbongan, Y., Sjahril, R., Pata'dungan, A. M., & Parari, T. Y. (2024). Genetic performance, heritability, and correlation of traits in new plant type of rice lines for highland ecosystem. Reproduction and Breeding, 4(4), 203–211. https://doi.org/10.1016/j.repbre.2024.08.002

Mukul , M. H. R., Hasan, M. M., Shamsunnaher, Zahan, A., Morshed, M. N., Ahmed, K. K., Biswash, M. R., Maniruzzaman, S., Kabir, M. H., & Karmakar, B. (2025). Yield Stability Evaluation of Antioxidant-Enriched Rice (*Oryza sativa* L.) Genotypes at Multi-Environments Using AMMI and GGE Biplot Model. Turkish Journal of Agriculture - Food Science and Technology, 13(5), 1152–1162. https://doi.org/10.24925/turjaf.v13i5.1152-1162.7391

Mukul, M. H. R., Shamsunnaher, S., Moniruzzaman, M., Zahan, A., Morshed, M. N., Ahmed, K. K., ... & Hasan, M. M. (2025). AMMI and WAASB-Based Stability Model Analysis for Identifying High-Yielding Stable Blast Resistant Rice (*Oryza sativa* L.) Genotype. Turkish Journal of Agriculture-Food Science and Technology, 13(s3), 3839-3848.

Nataraj, V., Bhartiya, A., Singh, C. P., Devi, H. N., Deshmukh, M. P., Verghese, P., Singh, K., Mehtre, S. P., Kumari, V., Maranna, S., Kumawat, G., Ratnaparkhe, M. B., Satpute, G. K., Rajesh, V., Chandra, S., Ramteke, R., Khandekar, N., & Gupta, S. (2021). WAASB-based stability analysis and simultaneous selection for grain yield and early maturity in soybean. Agronomy Journal, 113(4), 3089–3099. https://doi.org/10.1002/agj2.20750

Oladosu, Y., Rafii, M. Y., Abdullah, N., Magaji, U., Miah, G., Hussin, G., & Ramli, A. (2017). Genotype × Environment interaction and stability analyses of yield and yield components of established and mutant rice genotypes tested in multiple locations in Malaysia*. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 67(7), 590–606. https://doi.org/10.1080/09064710.2017.1321138

Oladosu, Y., Rafii, M. Y., Magaji, U., Abdullah, N., Miah, G., Chukwu, S. C., Hussin, G., Ramli, A., & Kareem, I. (2018). Genotypic and Phenotypic Relationship among Yield Components in Rice under Tropical Conditions. BioMed Research International, 2018. https://doi.org/10.1155/2018/8936767

Olivoto, T., Lúcio, Alessandro D.C., da Silva, J. A. G., 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. https://doi.org/10.2134/agronj2019.03.0220

Olivoto, T., Lúcio, A., Silva, J., Sari, B., & Diel, M. (2019). Mean Performance and Stability in Multi-Environment Trials II: Selection Based on Multiple Traits. Agronomy Journal, 111. https://doi.org/10.2134/agronj2019.03.0221

R Core Team. (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rahman, M. A., Afridi, S., Hossain, M. B., Rana, M., Al Masum, A., Rahman, M. M., & Al-Maruf, A. (2024). Nexus between heat wave, food security and human health (HFH): Developing a framework for livelihood resilience in Bangladesh. Environmental Challenges, 14, 100802. https://doi.org/10.1016/j.envc.2023.100802

Resende, M. D. V. D., & Alves, R. S. (2022). Statistical significance, selection accuracy, and experimental precision in plant breeding. Crop Breeding and Applied Biotechnology, 22(3), e42712238. https://doi.org/10.1590/1984-70332022v22n3a31

Shrestha, J., Subedi, S., Kushwaha, U. K. S., & Maharjan, B. (2021). Evaluation of growth and yield traits in rice genotypes using multivariate analysis. Heliyon, 7(9). https://doi.org/10.1016/j.heliyon.2021.e07940

Sruthi, K., Eswari, K. B., Damodhar Raju, C., Sheshu Madhav, M., Dhandapani, A., Senguttuvel, P., Bala Satya Sree, M., Sri Krishna Latha, K., Beulah, P., Nagaraju, P., Manasa, Y., Koteswararao, P., Sadath Ali, M., Divya, B., Revathi, P., Kemparaju, K. B., Jyothi, B., Sundaram, R. M., & Hari Prasad, A. S. (2024). Identification of stable restorer lines developed through inter-sub-specific hybridization in rice () using multi-trait stability index. Plant Breeding, 143(1), 105–119. https://doi.org/10.1111/pbr.13097

Supriadi, D., Bimantara, Y. M., Zendrato, Y. M., Widaryanto, E., Kuswanto, K., & Waluyo, B. (2024). Assessment of genotype by environment and yield performance of tropical maize hybrids using stability statistics and graphical biplots. PeerJ, 12, e18624. https://doi.org/10.7717/peerj.18624

Wei, S., Li, X., Lu, Z., Zhang, H., Ye, X., Zhou, Yujie, Li, J., Yan, Y., Pei, H., Duan, F., Wang, D., Chen, S., Wang, P., Zhang, C., Shang, L., Zhou, Yue, Yan, P., Zhao, M., Huang, J., … Zhou, W. (2022). A transcriptional regulator that boosts grain yields and shortens the growth duration of rice. Science, 377(6604), eabi8455. https://doi.org/10.1126/science.abi8455

Zhu, G., Wu, H., Chen, Y., Mondal, S., & Ismail, A. M. (2023). Growth characteristics and yield of contrasting rice genotypes under long-term stagnant flooding. Field Crops Research, 301, 109020. https://doi.org/10.1016/j.fcr.2023.109020

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Advancing Salinity-Tolerant Rice in Bangladesh: The Case of BRRI dhan67

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A B S T R A C T

Salinity is one of the major constraints limiting rice cultivation in the coastal regions of Bangladesh, where the rising salinity of soil and water continues to threaten crop productivity and food security. To address this challenge, Bangladesh Rice Research Institute (BRRI) developed BRRI dhan67, a salt-tolerant and high-yielding rice variety derived from a cross between IR61247-3B-8-2-1 and BRRI dhan36. This study summarizes the performance, adaptation, and dissemination of BRRI dhan67 based on multi-location adaptive research trials, participatory varietal selection, and post-release adaptation and out-scaling activities conducted from 2012 to 2022 across both saline and non-saline ecosystems of Bangladesh. BRRI dhan67 consistently performed well under varying levels of salinity stress, ranging from 4 to 12 deciSiemens per meter (dS/m), producing grain yield of 3.0 to 6.09 tons per hectare (t ha^{-1}) with an average of 4.47 t ha^{-1}. In non-saline environments, grain yield ranged from 5.42 to 7.53 t ha^{-1} with a mean of 6.62 t ha^{-1}. It showed robust seedling-stage salinity tolerance, maintaining 81% survival at 12 dS/m. Growth duration ranged from 138 to 144 days in the south coastal saline region, with an average of 141 days depending on different sites and seasons, while it ranged from 145 to 152 days with an average of 148 days in non-saline favorable environments. Grain quality assessments revealed superior milling recovery and head rice recovery, alongside medium-slender grain type and desirable cooking qualities. The variety also exhibited moderate resistance to major pests and diseases, adding to its agronomic stability. Participatory trials confirmed high farmer preference and strong adaptability in real-field conditions, particularly in salt-affected coastal zones. Overall, the results highlight BRRI dhan67 as a resilient and farmer-friendly solution with strong potential to enhance rice production and sustainability in both the saline-prone and favourable rice-growing environments of Bangladesh.

1. Introduction

The importance of rice transcends mere sustenance; it is a major determinant of food security and economic stability in many countries across the world. It is the most important staple crop, feeding almost half of the world's population (Hoang et al., 2016). In 2023, 168.35 million hectares of land were used for rice cultivation all over the world, and approximately 800 million tons of annual production was achieved (FAO, 2023). Approximately 90% of global rice is produced and consumed in Asia, marking sustainable rice production in Asia as a key decisive factor for global food security (Bandumula, 2018). Rice serves as a major source of rural employment and household earnings across the humid and semi-humid regions of

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Asia, supplying 50% to 80% of daily calories for more than three billion individuals (Hossain and Fischer, 1995). Eleven countries of Asia contribute about 87% to the total global rice production. About 503.17 MT of rice is produced worldwide, where China accounts for 29.5% of the total production, followed by India (23.8%), Bangladesh (7%), Indonesia (6.9%), and Vietnam (5.4%) (USDA, 2023). The world population is projected to reach about 9.6 billion by 2050, and about a 70% increase in production will be required to feed this population, indicating global cereal production must expand by an average of 44 million metric tons annually (Debsharma et al., 2024). Meeting this demand is severely constrained by climate change, biotic and abiotic stresses, reduced availability of cultivable land, and limited resources. Salinity and drought have been identified as the most critical abiotic stresses affecting global crop production (Munns, 2011). Around 20% of the total irrigated land of the world is suffering from a salinity problem (Munns, 2005). Nearly one-third of the world's arable land is saline-prone, and over half of all arable land may be under-salinized by 2050, making salinity a serious threat to the production of sustainable agriculture (Rahman et al., 2016, Shahid et al., 2017). The huge amount of potentially arable land in South and Southeast Asia remains unused because of salinity problems in the soil (Reddy et al., 2017). Bangladesh ranks as the third highest rice producing country in the world. Being a predominantly rice-growing nation, Bangladesh faces an increasing threat to its agricultural productivity due to salinity intrusion, particularly in coastal regions. Rising sea levels, tidal flooding, and reduced freshwater flows have intensified soil salinity, especially during the dry season (Boro season), affecting millions of hectares of arable land. In Bangladesh, salinity-affected areas extend over 2.85 million hectares in the southern coastal zone (Clarke et al., 2015), which contributes about 16% of the nation's total rice output (Debsharma et al., 2024). Among cereal crops, rice is the most susceptible to salinity stress, with concentrations as low as 30 mmol L^{-1} NaCl [equivalent to an electrical conductivity (EC) of 3 dS/m] significantly reducing its growth and yield (Lutts et al., 1995). At levels exceeding 3 dS/m, most modern high-yielding rice cultivars experience yield declines of around 12% per additional dS/m, with reductions of up to 50% observed at 6 dS/m (Linh et al., 2012). Salinity limits the photosynthetic ability and growth of rice plants, causing biomass loss, partial sterility, and ultimately resulting in reduced rice yield (Radanielson et al., 2018). Salt stress influences every stage of plant growth; however, in rice, the seedling and reproductive stages are the most vulnerable (Singh and Flowers, 2010). At the seedling stage, salinity reduces root and shoot length, while at the reproductive stage, it decreases tiller number, panicle length, spikelet fertility, and the number of spikes (Krishnamurthy et al., 2016). Plant responses to salt stress represent a complex process involving diverse physiological and biochemical alterations, such as changes in relative water status, electrolyte conductivity, accumulation of reactive oxygen species (ROS), nitrogen species, and other free radicals. These disturbances disrupt cellular homeostasis by interacting with biomolecules, impairing cell viability (Liu et al., 2017). Collectively, these effects hinder plant development and ultimately reduce yield.

Enhancing sustainable intensification of agricultural production in these salt-affected areas requires new rice varieties that possess tolerance to soil salinity. Traditional high-yielding rice varieties often underperform or fail to perform satisfactorily under saline conditions, creating an urgent need for varieties that can tolerate abiotic stress while maintaining yield and quality. Thus, development and dissemination of salt-tolerant rice varieties is considered as an economically viable strategy for securing food supplies (Qin et al., 2020).

To address this challenge, the Bangladesh Rice Research Institute (BRRI) developed the salt-tolerant breeding line BR7100-R-6-6, which was later released as BRRI dhan67 in 2014. The development process integrated advanced breeding techniques and involved a multi-phase evaluation strategy. The line underwent rigorous testing through station-based yield trials, multi-location Adaptive Research Trials (ALART), as well as Participatory Varietal Selection (PVS) involving direct farmer engagement across saline-prone regions. These evaluations not only confirmed its agronomic robustness but also assessed its acceptability among farmers and end-users in real-farming conditions.

Following its release, BRRI dhan67 was further evaluated through a large-scale adaptation and out-scaling initiative from 2017 to 2022, designed to validate its field performance and promote wider adoption. Using participatory and statistically robust trial designs, the initiative documented the variety's yield performance, growth duration, salt stress tolerance, grain quality traits, and farmer's preference-essential metrics for determining its practical value.

The present study consolidates findings from both pre- and post-release evaluations of BRRI dhan67 conducted, offering a comprehensive overview of its agronomic performance, resilience, grain quality and suitability for scaling across stress-prone rice-growing ecosystems of Bangladesh.

2. Materials and methods

The vegetative stage salt-tolerant and moderately cold-tolerant, high-yielding rice variety BRRI dhan67 originated from a single cross between the parental lines IR61247-3B-8-2-1 and BRRI dhan36. The parental combination was intended to combine salinity tolerance with shorter growth duration, cold tolerance, and improved grain quality. Both the pedigree selection method and the Rapid Generation Advance

(RGA) technique were adopted in the breeding process to accelerate homozygosity and genetic fixation. After fixation of the genotype, the resulting advanced line was designated as BR7100-R-6-6. The selected line BR7100-R-6-6, showed promising traits and was subjected to a rigorous multi-phase evaluation pipeline conducted at BRRI, Gazipur, and in the saline-prone southern coastal region of Bangladesh.

Following the primary yield trials (OYT, PYT, SYT, etc.), the advanced line was included in the Regional Yield Trial (RYT) for testing along with other promising advanced lines and check varieties. Subsequently, it entered the Advanced Lines Adaptive Research Trial (ALART) conducted in six key salinity-affected sites: Debhata, Kaliganj, Shyamnagor (Satkhira); Kalapara (Patuakhali); Amtoli (Barguna); Paikgacha (Khulna); and in one non-stress environment, Gazipur. EC of the trial fields was monitored, and the trial was managed by the Adaptive Research Division of BRRI. Data like survivability (%) and salt tolerance score of the proposed line against susceptible check (BRRI dhan28) and tolerant check (BRRI dhan47), yield, different agronomic traits, insect, disease occurrence scoring, water salinity (dS/m) level, and overall adaptability of the line were evaluated.

In conventional plant breeding programs, new crop varieties are usually developed in optimal and controlled settings, which hardly reflect the marginal farm conditions and fail to perform well in stress-prone areas. To ensure adaptability under real-farming stress conditions, such as sodic soils, the advanced breeding line BR7100-R-6-6 was evaluated through Participatory Varietal Selection (PVS), a participatory approach that addresses this gap by actively involving the farmers in the evaluation and selection process during 2012-2013 using a mother-and-baby trial, enhancing relevance and adoption. It ensures that the developed varieties are well-adapted to the stress environment and meet the demands of the farming community. A validation trial was also carried out at that time. A group of farmers was invited to assess the varietal performance in the trial. Before evaluation, the objectives and layout of the trial were clearly explained. Farmers were given two positive (√) and two negative (×) ballots to vote for their most and least preferred varieties, respectively. They independently walked through the trial plots, observed plant characteristics, and submitted ballots for (a) the variety they would most like to grow and (b) the one they would least prefer, and provided qualitative feedback on varietal traits. After voting, ballots were counted jointly by researchers and farmers. A preference score (PS) was determined for each variety by calculating the number of positive votes minus the number of negative votes, divided by the total number of votes cast by the farmers. The preference score (PS) for each variety was calculated as follows:

$$PS = \frac{\text{Number of positive votes- negative votes}}{\text{Total number of positive and negative votes}}$$

The group then revisited the most liked and least liked varieties to discuss their strengths and weaknesses. This qualitative feedback provided valuable insights into farmers' priorities, including yield potential, plant vigor, disease resistance, and grain quality. This participatory evaluation facilitated farmer-centric decision-making and supported the advancement of BR7100-R-6-6 based on both agronomic performance and end-user acceptance.

Based on the superior performance of BR7100-R-6-6 in PVS and ALART, it was advanced to the Proposed Variety Trial (PVT) in the subsequent Boro 2013-2014 season. PVT trial was conducted in 10 locations of the southern saline belt, where it was evaluated against the tolerant check BRRI dhan47. Performance of the proposed line was recorded at different salinity gradients ranging from 0 dS/m to almost 15 dS/m, along with plant height (cm) and growth duration (days). Additionally, the grain quality traits such as amylose content (%), protein content (%), 1000-grain weight (g), milling recovery (%), head rice recovery (%), and the length-breadth ratio of decorticated grains were analyzed to assess their market and consumer acceptability. Reaction of the proposed line towards major diseases and insect pests was also evaluated under natural field conditions, and scoring was done based on the International Rice Research Institute (IRRI) Standard Evaluation System (SES) protocol.

Following its official released in 2014, an extensive adoption and out-scaling initiative was undertaken from 2017 to 2022 to validate the adaptability of BRRI dhan67 in different environments at farmers' fields and for its rapid dissemination. During this period, a total of 150 adaptive trials and a seed production and dissemination program were conducted across 44 upazilas in 16 districts, covering an area of approximately 50.2 hectares of land, including both saline and non-saline areas like the coastal regions of Khulna, Satkhira, Barguna, and Patuakhali, as well as inland zones like Jashore and Faridpur. Each trial comprised one to three bighas of land (0.13–0.4 ha) and was supported with inputs such as seeds, fertilizers, pesticides, signboards, and labor. Fertilizers were applied at recommended doses of N, P, K, S, and Zn at 125, 22, 75, 20, and 2.7 kg ha^{-1}, respectively, using urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum, and zinc sulfate (BRRI, 2025). TSP, gypsum, zinc sulfate, and two-thirds of MoP were applied as basal during land preparation. Urea was top-dressed in three equal splits at 15, 30, and 45 days after transplanting (DAT), while MoP was top-dressed along with the third top dressing of urea. Yield and agronomic data were collected from each site. Field water salinity levels (dS/m) were monitored at critical growth stages using standard EC meters. Data collected from the trials were analyzed using the software Statistix 10.

3. Results and discussion

The PVS trial was conducted across five saline-prone coastal sites in the Patuakhali and Barguna districts. Among the tested genotypes and varieties, BR7100-R-6-6 outperformed the others by achieving the highest yield in three locations. Across the coastal sites of Bazarkhali, Sharikhali, and Pasharibunia, it demonstrated strong performance, yielding between 4.9 and 7.2 t ha^{-1} with an average of 6.3 t ha^{-1} under salinity stress conditions. In addition to yield, the genotype showed favourable growth duration and plant stature, reaching maturity in 144 days with an average plant height of 108.8 cm (Table 1). In PVS preference analysis, based on farmers' vote, BR7100-R-6-6 ranked among the top two preferred genotypes in two locations (Table 2). The preference ranking was different from location to location and yield was not the only criterion for varietal selection. It indicated that, along with its high yield potential, the proposed line also carried characteristics that matched farmers' choice and preferences, ensuring its better adaptability in that region. Thus, PVS seemed to be a favored method for confirming varieties appropriate for stress-prone regions because farmers are actively involved in selecting the variety they want (Sharma et al., 2013, Singh et al., 2014). The subsequent validation trial conducted at Sharikhali, Pasharibunia, and Paschim Rajopara reconfirmed the finding that BR7100-R-6-6 is highly compatible for the saline-prone region of Bangladesh, as it produced the highest mean yield of 6.1 t ha^{-1}. Moreover, the other agronomic traits were also obtained within preferred ranges (Table 3).

The adaptability of the proposed line was assessed under diverse salinity levels through the ALART trial conducted across seven locations, emphasizing the saline-prone regions of the country. The proposed line produced an average grain yield of 5.8 t ha^{-1}, with site-specific yields ranging from 3.6 t ha^{-1} at Debhata (EC: 2.85–5.48 dS/m) to 6.9 t ha^{-1} at Amtoli (EC: 0.56–0.79 dS/m). The check variety BRRI dhan47 recorded a slightly higher overall mean yield of 6.0 t ha^{-1} compared to BR7100-R-6-6. The performance of BR7100-R-6-6 was comparable with the check BRRI dhan47 at most of the locations, particularly at Paikgacha, achieving 4.8 t ha^{-1} yield, where it faced the highest salinity stress in the trial (EC: 3.71–9.56 dS/m) (Table 4 and Table 5). It also showed a two-day shorter growth duration than the check variety. Along with satisfactory yield and agronomic performance, BR7100-R-6-6 exhibited the highest survivability (81%) and comparable salt tolerance score (5.0) at the seedling stage to the check variety BRRI dhan47 (5.2) when exposed to an EC level of 12 dS/m (Table 6). This trait is particularly critical for ensuring crop establishment in coastal regions where saline water intrusion frequently affects germination and seedling establishment. The results indicated that BR7100-R-6-6 combines stability across stress gradients, early-stage salinity resilience, and competitive yield performance, making it suitable for the coastal and salinity-affected rice-growing regions of Bangladesh.

Based on the performance of the genotype in PVS trial and ALART, it was recommended to Proposed Variety Trial (PVT) during Boro 2013-2014. The proposed line was evaluated in ten different saline-affected regions under PVT to validate its performance (Table 7) with changes in salinity levels tracked over time (Fig. 1). Across all test locations, BR7100-R-6-6 achieved an average yield of 5.98 t ha^{-1}, clearly outperforming the salt-tolerant check BRRI dhan47, which averaged 5.48 t ha^{-1}. In fact, BR7100-R-6-6 out-yielded BRRI dhan47 in nine locations out of 10 locations, showing especially high productivity at Tala (7.27 t ha^{-1}), BRRI Satkhira Farm (7.48 t ha^{-1}), and Sonagazi (7.0 t ha^{-1}). The results showed that the proposed line has the potential to produce almost 7.5 t ha^{-1} grain yield when faced with a lower level of salinity. Batiaghata experienced the highest salinity stress, with EC levels rising from 9 to 14.5 dS/m during February to April, yet BR7100-R-6-6 still managed to outperform the check variety BRRI dhan47 by delivering a 16% higher yield at that site. These results pointed to its strong adaptability and reliable performance under varying saline conditions.

Different physico-chemical and grain quality attributes of the proposed line and the check variety BRRI dhan47 are presented in Table 8 to assess market and consumer acceptability. Although BR7100-R-6-6 showed a lower 1000-grain weight (20.9 g) than BRRI dhan47 (25.9 g), PVT results showed that this character did not compromise the yield advantage of the line. BR7100-R-6-6 showed better milling recovery (69.4%) and significantly higher head rice recovery (71.1%) compared to BRRI dhan47 (44.2%), indicating production of more finished rice, lower breakage, and higher whole grain retention after milling. Medium slender grain type of BR7100-R-6-6 makes it more desirable to the consumers than the medium bold grain type of BRRI dhan47. The protein content (8.8%) and amylose content (24.6%) of the genotype were found to be within an acceptable standard. All these traits highlight the proposed line's potential not just as a high-yielding, salt-tolerant variety, but also as one with improved grain quality that satisfies both market demands and consumer preferences, making it a strong, all-around candidate for widespread cultivation.

The proposed line BR7100-R-6-6 was tested for major diseases and insect pests in natural field conditions, and its performance was compared with the check variety BRRI dhan47 (Table 9). In the field, BR7100-R-6-6 showed excellent resistance to bacterial blight, scoring just 1, indicating high resistance; meanwhile, BRRI dhan47 was more vulnerable with a score of 7. The proposed line also showed moderate resistance (score 3) to other key threats like blast, dead heart, and white head, in contrast to BRRI dhan47, which scored 7 and 5 for the same parameters, indicating moderate susceptibility. Overall, BR7100-R-6-6 offered a stronger and more balanced defense against multiple pests and diseases, which adds to its appeal for farmers looking for a reliable, lower-maintenance variety in challenging environments. On the other hand, the Distinctness, Uniformity and Stability (DUS) test is essential for the release and registration of new varieties of notified crops. Distinguishing characters of the proposed line, BR7100-R-6-6 compared to BRRI dhan28 are flag leaf: attitude of blade, culm: length, panicle: number of effective tillers in a hill, grain: length (without dehulling), decorticated grain: length (After dehulling, before milling), decorticated grain: shape (Length-breadth ratio) and endosperm: content of amylose (Table 10). No notable change or segregation was observed in the test plots of two consecutive seasons of testing at the Seed Certification Agency (SCA) farm in Gazipur, suggesting that the proposed line is stable. In light of its consistent performance and adaptability across saline environments, the National Seed Board of Bangladesh approved the recommendation of the technical committee to officially release the proposed line, BR7100-R-6-6, as a salt-tolerant Boro variety, BRRI dhan67, for cultivation in saline-affected regions in 2014.

The adaptability of BRRI dhan67 was extensively evaluated through a multi-location adaptive trial, which comprised almost 150 trials across 16 districts of the country covering almost 50 ha of land in both saline and non-saline regions for six consecutive years (2017-2022). It provided a clear insight into how environment, genotype, and cropping year, and their interactions significantly influenced the performance of BRRI dhan67 (Karmakar et al., 2019). In saline areas, the variety produced an average yield of 4.47 t ha^{-1} while the site-specific yield ranged from 3.0 t ha^{-1} to 6.09 t ha^{-1} (Table 11), and salinity stress level varied from 4 dS/m to 12 dS/m. In severely saline-affected areas, such as Rampal, Koyra, and Shyamnagar, where the EC exceeded 8 dS/m, BRRI dhan67 recorded its lowest yield: 3.0 t ha^{-1}, 3.38 t ha^{-1}, and 3.5 t ha^{-1}, respectively (Fig. 2). In contrast, under non-saline conditions, the variety demonstrated its full potential, yielding an average of 6.62 t ha^{-1}, highest at 7.53 t ha^{-1} in Keshabpur and 7.50 t ha^{-1} in Batiaghata. Mean grain yield (6.62 t ha^{-1}) of BRRI dhan67 under a non-saline environment was significantly higher than in a saline environment (4.47 t ha^{-1}) (Tables 12 and 13). Generally, grain yield was always higher in non-saline environments compared to saline environments (Nayak et al., 2022). These data highlighted the clear performance of the climate-resilient variety BRRI dhan67 in both the stress-prone and favorable environments.

The environment had a notable impact on growth duration. In saline areas, BRRI dhan67 matured in about 141 days on average, while in non-saline environments, it took an average of 148 days to maturity. Growth duration ranged from 138 to 152 days across the environments. The lowest duration (138 days) was counted at the saline environment at Chakaria, Cox's Bazar, followed by Kaliganj, Satkhira (139 days), likely due to faster crop development in stress-affected environments. When grown in non-saline, favorable conditions, but comparatively prolonged winter existing environments (Parbatipur and Birganj, Dinajpur), the growth duration of the variety was extended up to 152 days (Fig. 3). Interestingly, while conducting extensive multi-location adaptive trials, BRRI dhan67 was found to be moderately tolerant against vegetative stage cold, particularly during the seedling stage.

These trials also contributed significantly to seed dissemination and farmer awareness. Across all locations, around 285 tons of grain were harvested, of which 54 tons (16%) were saved as seed. Interestingly, seed retention was proportionally higher in saline areas (19%) than in non-saline areas (14%), indicating stronger engagement in stress-prone zones. A total of 7,597 farmers were reached through these trials, with 1,426 (18%) showing immediate interest in adopting BRRI dhan67. The percentage of motivated farmers was also higher in saline areas (20%) compared to non-saline areas (17%), despite the latter hosting more trials (Table 13). Consequently, the adaptive trials played an important role in generating quantitative information and enhancing the adoption of BRRI dhan67 in both the saline and non-saline environments (Karmakar et al., 2021).

Overall, these findings confirmed the robustness and adaptability of BRRI dhan67 across a range of environments. Its stable performance in saline soils, coupled with its favorable growth duration and high acceptance among farmers, underscores its suitability for both marginal coastal and favourable rice-growing ecosystems in Bangladesh.

Table 1
Performance of genotypes in PVS at different locations of Patuakhali and Barguna in Boro season 2012-2013.

Serial number	Genotype	Duration (days)	Plant height (cm)	Yield (t/ha)					
				Baz	Sha	Par	Rajo	P. Rajo	Mean
1	BR7100-R-6-6	144	108.8	7.2	7.2	6.0	4.9	6.3	6.3
2	IR89578-84	143	104.2	6.7	6.8	-	4.7	-	6.1
3	IR59418-7B-21-3	143	91.0	6.5	6.9	5.5	3.9	6.4	5.8
4	IR78794-B-SAT29-1	146	98.0	6.9	6.5	5.5	4.4	5.9	5.8
5	BRRI dhan28	141	100.0	6.9	6.7	5.4	4.6	5.5	5.8
6	BRRI dhan47	147	99.7	6.7	6.6	5.8	4.4	5.2	5.8
7	BRRI dhan55	143	96.9	7.2	6.5	5.7	5.1	5.5	6.0

Baz = Bazarkhali; Sha = Sharikhali; Par = Pasharibunia; Rajo = Rajopara; P. Rajo = Pashchim Rajopara.

Table 2
Farmers' preference analysis of mother trial for rice genotypes grown at different locations at Patuakhali and Barguna in Boro season 2012-2013.

Location/PVS	Farmers preference ranking and score			
	1st +ve	2nd +ve	1st -ve	2nd -ve
Rajopara, Kolapara, Patuakhali (PVS-2)	BRRI dhan47 (0.208)	BR7100-R-6-6 (0.116)	IR59418-7B-21-3 (-0.233)	IR78794-B-Sat29-1 & BRRI dhan55 (-0.108)
Pashchim Rajopara, Kolapara, Patuakhali (PVS-2)	BRRI dhan47 (0.058)	BRRI dhan28 (0.033)	IR59418-7B-21-3 (-0.166)	IR78794-B-Sat29-1 (-0.008)
Sharikhali, Sadar, Patuakhali (PVS-2)	BRRI dhan28 (0.133)	IR89578-84 (0.025)	IR78794-B-Sat29-1 (-0.125)	BR7100-R-6-6 (-0.025)
Pashribunia, Sadar, Patuakhali (PVS-2)	BRRI dhan28 (0.191)	BR7100-R-6-6 (0.150)	IR78794-B-Sat29-1 (-0.175)	BRRI dhan47 (-0.158)
Bazarkhali, Amtoli, Barguna (PVS-2)	IR89578-84 (0.150)	BRRI dhan47 (0.083)	IR59418-7B-21-3 (-0.183)	IR78794-B-Sat29-1 (-0.043)

Farmers' preference score put in parenthesis.

Table 3
Agronomic performances of the salt-tolerant genotypes in validation trial at different locations in Boro season 2012-2013.

Serial number	Genotype	Duration (days)	PH (cm)	Yield (t/ha)			
				Sharikhali	Pasharibunia	P. Rajopara	Mean
1	BR7100-R-6-6	146	109.7	7.0	5.8	5.4	6.1
2	IR59418-7B-21-3	144	87.5	6.7	5.8	5.8	6.1
3	IR78794-B-SAT-29-1	146	97.5	6.3	5.5	5.7	5.9

PH = Plant height; P. Rajopara = Pashchim Rajopara.

Table 4
Performance of the proposed line at different zonal trials (Adaptive trial) in Boro season 2012-2013.

Genotype	GD*	Yield (t/ha)							
		L1	L2	L3	L4	L5	L6	L7	Mean
BR7100-R-6-6	150	3.6	6.4	6.3	6.5	6.9	4.8	6.3	5.8
BRRI dhna47 (Ck)	152	5.8	6.5	5.6	6.3	4.9	6.2	6.9	6.0

L1 = Debhata, Satkhira; L2 = Kaliganj, Satkhira; L3 = Shyamnagar, Satkhira; L4 = Kalapara, Patuakhali; L5 = Amtoli, Barguna; L6 = Paikgacha, Khulna; L7 = Gazipur
*GD = Growth duration; Mean of seven locations

Table 5
Water salinity/electrical conductivity (EC) range at on-farm adaptive trial (ALART) for experimental period in Boro season 2012-2013.

Location	Water salinity/EC (dS/m) range
Debhata, Satkhira	2.85-5.48
Kaligonj, Satkhira	3.65-5.52
Shyamnagor, Satkhira	2.15-4.13
Kalapara, Patuakhali	1.05-1.50
Amtoli, Barguna	0.56-0.79
Paikgacha, Khulna	3.71-9.56
Asasuni, Satkhira	2.63-6.20

Table 6
Salinity tolerance score and survivability of the proposed variety following IRRI SES at EC of 12 dS/m at the seedling stage in Boro season 2012-2013.

Proposed line with standard check	Salinity tolerance score	Survivability (%)
BR7100-R-6-6 (Proposed)	5.0	81
BRRI dhan28 (Ck)	7.0	42
BRRI dhan47 (Ck)	5.2	75

Table 7
Yield and agronomic performance of the proposed lines in the Proposed Variety Trial (PVT) in Boro season 2013-14.

Proposed line with standard check	Plant height (cm)	Growth* duration (days)	Yield (t/ha)										
			L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	Mean
BR7100-R-6-6 (Proposed)	100	143	5.29	5.57	3.81	6.94	5.38	7.27	7.48	7.00	5.60	5.42	5.98
BRRI dhan47 (Ck)	105	144	4.32	4.81	3.28	6.40	5.83	7.16	7.44	6.20	4.69	4.71	5.48

L1 = Dakope; L2 = Paikgacha; L3 = Batiaghata, Khulna; L4 = Asasuni; L5 = Debhata; L6 = Tala; L7 = BRRI farm, Satkhira; L8 = Sonagazi, Feni; L9 = Patharghata, Barguna; L10 = Nazirpur, Pirojpur
*Mean of 10 locations

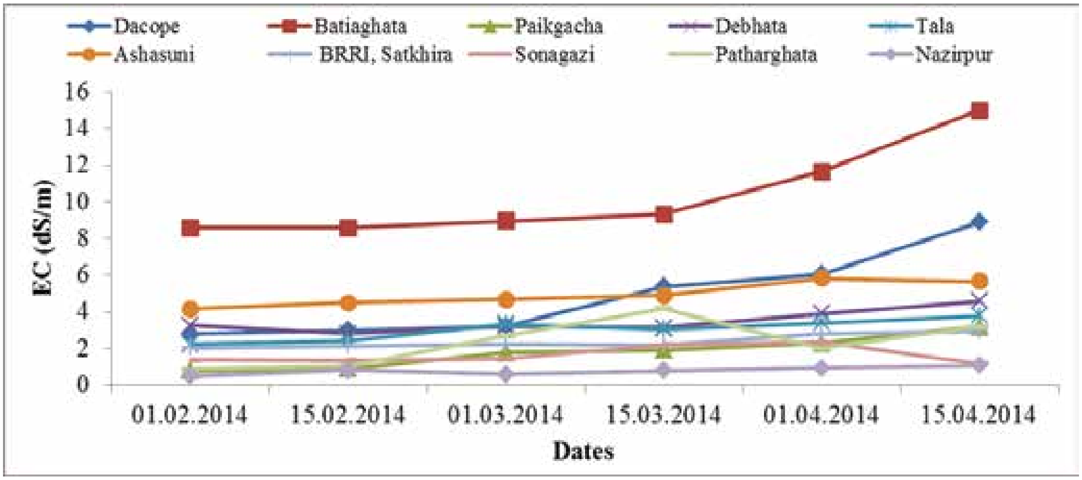

Fig. 1. Water salinity levels (dS/m) of different experimental plots during the proposed variety trials in Boro season 2013-2014.

Table 8
Physico-chemical and grain characteristics of proposed lines and standard check.

Proposed line with standard check	1000 grain weight (g)	Milling recovery (%)	Head rice yield (%)	Decorticated grain				ER	IR	Cooking time (min)	Protein (%)	Amylose (%)
				Length (mm)	Breadth (mm)	L/B	Size and shape					
BR7100-R-6-6 (Proposed)	20.9	69.4	71.1	5.9	2.1	2.8	MS	1.3	2.7	16.30	8.8	24.6
BRRI dhan47 (Ck)	25.9	67.6	44.2	5.4	2.7	2.0	MB	1.4	3.6	17.00	8.2	27.5

ER = Elongation ratio, IR = Imbibition ratio, MS = Medium slender, MB = Medium bold.

Table 9
Reaction of the proposed line against major diseases and insects under natural field conditions during Boro 2013-14.

Proposed line with standard check	Disease reaction		Insect reaction	
	BB	Blast	DH	WH
BR7100-R-6-6 (Proposed)	1	3	3	3
BRRI dhan47 (Ck)	7	7	5	5

BB = Bacterial blight; DH = Dead heart; WH = White head.

Table 10
Distinctness between BR7100-R-6-6 (Proposed line) and BRRI dhan28.

SL	Characteristics	BR7100-R-6-6 (Proposed line)		BRRI dhan28 (Check variety)		Remarks
		Code	State	Code	State	
1	Flag leaf: attitude of the blade	3	Semi erect	5	Horizontal	Distinct
2	Culm: Length	7	Long	5	Medium	Distinct
3	Panicle: number of effective tillers in a hill	7	Many	5	Medium	Distinct
4	Grain: length (without dehulling)	7	Long	9	Very Long	Distinct
5	Decorticated grain: length (After dehulling, before milling)	3	Medium	5	Long	Distinct
6	Decorticated grain: shape (Length-breadth ratio)	7	Medium slender	9	Slender	Distinct
7	Endosperm: content of amylose	3	Intermediate	5	High	Distinct

Table 11
Descriptive Statistics of BRRI dhan67 for saline environment during 2018 to 2022 Boro seasons at different districts of Bangladesh.

Variable	Growth duration (days)	Grain yield (t ha^{-1})	Total production (ton)	Seed retained		Knowledge sharing farmer (number)	Motivated farmer	
				ton	(%)		number	(%)
Mean	141	4.47	2.78	0.61	19	91	18	20
Minimum	138	3.00	1.36	0.00	0	64	5	6
Median	141	4.43	2.38	0.42	18	89	18	19
Maximum	144	6.09	4.89	2.15	50	161	38	37
Sum	5069	161.94	99.91	21.95	685	3278	656	710
N	36	36	36	36	36	36	36	36
SD	1.45	0.73	1.12	0.59	14.19	19.94	8.87	8.29
Variance	2.10	0.53	1.24	0.4	201.3	397.5	78.8	68.9
SE Mean	0.24	0.12	0.19	0.10	2.36	3.32	1.48	1.38
CV (%)	1.0	16.3	40.2	97.1	74.6	21.9	48.7	42.1

N = Number of trials; SD = Standard deviation; SE = Standard error; CV = Co-efficient of variation.

Table 12
Descriptive Statistics of BRRI dhan67 for non-Saline environment during 2018 to 2022 Boro seasons at different districts of Bangladesh.

Variable	Growth duration (days)	Grain yield (t ha^{-1})	Total production (ton)	Seed retained		Knowledge sharing farmer (number)	Motivated farmer	
				ton	(%)		number	(%)
Mean	148	6.62	4.51	0.78	14	105	19	17
Minimum	145	5.42	2.18	0.00	0	64	5	5
Median	148	6.67	3.02	0.31	9	102	15	16
Maximum	152	7.53	11.33	5.60	54	154	53	35
Sum	6067	271.22	184.73	31.86	561	4319	770	694
N	41	41	41	41	41	41	41	41
SD	1.9	0.5	2.5	1.1	12.7	27.9	11.2	6.4
Variance	3.42	0.24	6.28	1.30	160.82	779.03	125.58	40.77
SE Mean	0.29	0.08	0.39	0.18	1.98	4.36	1.75	1.00
CV (%)	1.25	7.40	55.62	146.9	92.68	26.50	59.67	37.72

N = Number of trials; SD = Standard deviation; SE = Standard error; CV = Co-efficient of variation.

Table 13
Results of BRRI dhan67 in saline and non-saline environments during 2018 to 2022 Boro seasons at different districts of Bangladesh.

Environment	Area		Mean growth duration (day)	Mean grain yield (tha^{-1})	Total production (ton)	Seed retained		Knowledge sharing farmer (number)	Motivated farmer	
	bigha	ha				ton	%		number	(%)
Saline	168.0	22.5	141	4.47	100	22	19	3278	656	20
Non-saline	207.0	27.7	148	6.62	185	32	14	4319	770	17
Grand mean	-	-	145	5.61	-	-	16	-	-	18
Grand total	375.0	50.2	-	-	285	54	-	7597	1426	-
LSD (0.05)	-	-	1.9	0.76	2.0	1.0	-	-	-	-
CV (%)	-	-	1.1	11.4	-	-	-	-	-	-

Ha = hectare; LSD = Least significant difference; CV = Co-efficient of variation.

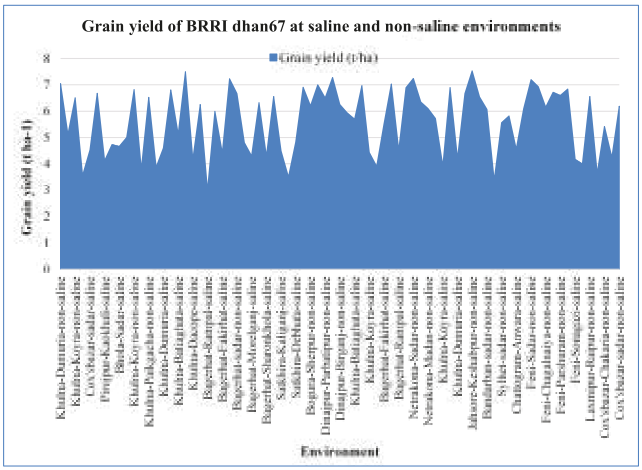

Fig. 2. Grain yield of BRRI dhan67 in saline and non-saline environments during 2018 to 2022 Boro seasons at different districts of Bangladesh.

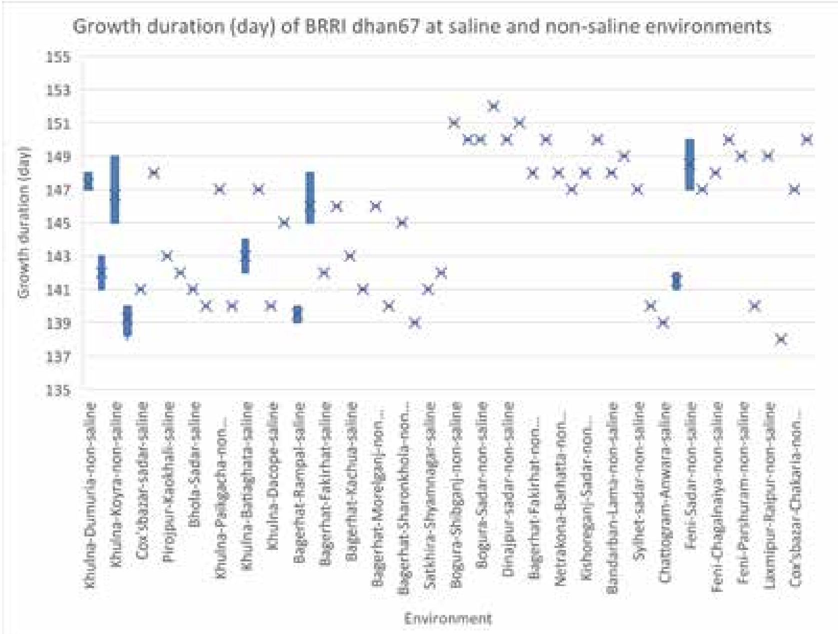

Fig. 3. Growth duration of BRRI dhan67 in saline and non-saline environments during 2018 to 2022 Boro seasons at different districts of Bangladesh.

4. Conclusion

The comprehensive multi-environment evaluation of BRRI dhan67 confirmed its strong potential as a stable and robust salt-tolerant Boro rice variety for the coastal agro-ecosystems of Bangladesh. Across both pre- and post-release phases, the variety consistently demonstrated stable grain yield, shorter growth duration, and strong adaptability to varying salinity levels, ranging from moderate to high (up to 15 dS/m). BRRI dhan67 not only outperformed the widely accepted check variety BRRI dhan47 in most trial sites, but also offered improved grain quality traits, such as better milling recovery, higher head rice recovery, and preferred slender grain type. Furthermore, its resistance to key diseases and insect pests, coupled with strong farmer preference in participatory trials, indicated its practicality and acceptance at the grassroots level. The post-release adaptation and out-scaling trials highlighted its scalability and practical utility, particularly in saline-prone regions where seed retention and farmer motivation were notably high. Overall, BRRI dhan67 represents a significant advancement in climate-resilient rice breeding, offering a viable solution to sustain rice production and enhance food security in vulnerable coastal regions of Bangladesh.

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References

Bandumula, N. (2018). Rice production in Asia: Key to global food security. Proceedings of the National Academy of Sciences, India, Section B: Biological Sciences, 88(4), 1323–1328.

Bangladesh Rice Research Institute. (2025). Modern rice cultivation (Adhunik dhaner chash), 25th ed., pp. 5–125.

Clarke, D., Williams, S., Jahiruddin, M., Parks, K., & Salehin, M. (2015). Projections of on-farm salinity in coastal Bangladesh. Environmental Science: Processes & Impacts, 17(6), 1127–1136.

Debsharma, S. K., Rahman, M. A., Khatun, M., Disha, R. F., Jahan, N., Quddus, M. R., Khatun, H., Dipti, S. S., Ibrahim, M., Iftekharuddaula, K. M., & Kabir, M. S. (2024). Developing climate-resilient rice varieties (BRRI dhan97 and BRRI dhan99) suitable for salt-stress environments in Bangladesh. PLoS ONE, 19(1), e0294573. https://doi.org/10.1371/journal.pone.0294573

Food and Agriculture Organization of the United Nations. (2023). Production/yield quantities of rice, paddy in world. FAOSTAT. https://www.fao.org/faostat/en/#QC (accessed on 23 September 2025).

Hoang, T. M. L., Tran, T. N., Nguyen, T. K. T., Williams, B., Wurm, P., Bellairs, S., & Mundree, S. (2016). Improvement of salinity stress tolerance in rice: Challenges and opportunities. Agronomy, 6(4), 54.

Hossain, M., & Fischer, K. S. (1995). Rice research for food security and sustainable agricultural development in Asia: Achievements and future challenges. GeoJournal, 35(3), 286–298.

Karmakar, B., Mamun, M. A. A., Rahman, M. S., Islam, M. A., Islam, M. R., Mukul, M. H. R., Shamsunnaher, Zahan, A., Barua, R., Biswas, M. R., Parveen, S., Akter, S., Shaikh, N. Y., & Ahmed, B. (2019). Adaptation of promising rice genotypes for broadcast Aus season. Bangladesh Rice Journal, 23(2), 35–48. https://doi.org/10.3329/brj.v23i2.48246

Karmakar, B., Rahman, M. M., Sarkar, M. A. R., Mamun, M. A. A., Rahman, M. C., Nessa, B., Salam, M. U., & Kabir, M. S. (2021). Adoption lag minimization for increasing rice yield. Bangladesh Rice Journal, 25(1), 75–88. https://doi.org/10.3329/brj.v25i1.55180

Krishnamurthy, S. L., Gautam, R. K., Sharma, P. C., & Sharma, D. K. (2016). Effect of different salt stresses on agro-morphological traits and utilization of salt stress indices for reproductive stage salt tolerance in rice. Field Crops Research, 190, 26–33.

Linh, L. H., Linh, T. H., Xuan, T. D., Ham, L. H., Ismail, A. M., & Khanh, T. D. (2012). Molecular breeding to improve salt tolerance of rice (*Oryza sativa* L.) in the Red River Delta of Vietnam. International Journal of Plant Genomics, 2012(1), 949038.

Liu, S., Hao, H., Lu, X., Zhao, X., Wang, Y., Zhang, Y., & Wang, R. (2017). Transcriptome profiling of genes involved in induced systemic salt tolerance conferred by Bacillus amyloliquefaciens FZB42 in Arabidopsis thaliana. Scientific Reports, 7(1), 10795.

Lutts, S., Kinet, J. M., & Bouharmont, J. (1995). Changes in plant response to NaCl during development of rice (*Oryza sativa* L.) varieties differing in salinity resistance. Journal of Experimental Botany, 46(12), 1843–1852.

Munns, R. (2005). Genes and salt tolerance: Bringing them together. New Phytologist, 167(3), 645–663.

Munns, R. (2011). Plant adaptations to salt and water stress: Differences and commonalities. Advances in Botanical Research, 57, 1–32.

Nayak, S., Habib, M. A., Das, K., Islam, S., Hossain, S. M., Karmakar, B., Fritsche, R. N., Bhosale, S., Bhardwaj, H., Singh, S., et al. (2022). Adoption trend of climate-resilient rice varieties in Bangladesh. Sustainability, 14, 5156. https://doi.org/10.3390/su1409515

Qin, H., Li, Y., & Huang, R. (2020). Advances and challenges in the breeding of salt-tolerant rice. International Journal of Molecular Sciences, 21(21), 8385.

Radanielson, A. M., Angeles, O., Li, T., Ismail, A. M., & Gaydon, D. S. (2018). Describing the physiological responses of different rice genotypes to salt stress using sigmoid and piecewise linear functions. Field Crops Research, 220, 46–56.

Rahman, M. A., Thomson, M. J., Shah-E-Alam, M., de Ocampo, M., Egdane, J., & Ismail, A. M. (2016). Exploring novel genetic sources of salinity tolerance in rice through molecular and physiological characterization. Annals of Botany, 117(6), 1083–1097. https://doi.org/10.1093/aob/mcw030 PMID: 27063367

Reddy, I. N. B. L., Kim, S. M., Kim, B. K., Yoon, I. S., & Kwon, T. R. (2017). Identification of rice accessions associated with K^+/Na^+ ratio and salt tolerance based on physiological and molecular responses. Rice Science, 24, 360–364. https://doi.org/10.1016/j.rsci.2017.10.002

Shahid, S. A., Zaman, M., & Heng, L. (2018). Soil salinity: Historical perspectives and a world overview of the problem. In Guidelines for salinity assessment, mitigation and adaptation using nuclear and related techniques (pp. 43–53). Springer International Publishing, Switzerland.

Sharma, N., Sarker, M. R. A., Rahman, M. A., & Islam, M. R. (2013). Participatory varietal selection of modern T. Aman rice varieties in salt-affected coastal area of Bangladesh. Eco-friendly Agriculture Journal, 6(8), 141–145.

Singh, R. K., & Flowers, T. J. (2010). The physiology and molecular biology of the effects of salinity on rice. In Handbook of plant and crop stress (pp. 899–939). Marcel Dekker, Inc. New York.

Singh, Y. P., Nayak, A. K., Sharma, D. K., Gautam, R. K., Singh, R. K., Singh, R., & Ismail, A. M. (2014). Farmers' participatory varietal selection: A sustainable crop improvement approach for the 21st century. Agroecology and Sustainable Food Systems, 38(4), 427–444.

United States Department of Agriculture. (2023). Rice production by country—World agricultural production 2023/2024. World Agricultural Production. http://www.worldagriculturalproduction.com/crops/rice.aspx (accessed on 23 September 2025).

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Genetic Diversity and Population Structure in Wild Rice Germplasm

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A B S T R A C T

Wild rice species are rich sources of useful allelic variation for genetic improvement of cultivated rice for improvement of yield and yield-related traits and biotic and abiotic stress tolerance. The study of genetic diversity and population structure is a crucial measure for the proper utilization of available genetic resources in a plant breeding program. Seventy-seven wild rice and relatives collected from International Rice Research Institute and different regions of Bangladesh were investigated using 42 simple sequence repeat (SSR) markers to unveil the population structure and to estimate genetic diversity. A total of 200 alleles were detected, with an average of 4.76 alleles per locus. Besides, 19 unique alleles were found with 16 SSR markers, which can be used as diagnostic tools for germplasm identification. A comparative assessment of STRUCTURE and UPGMA showing a high level of concordance in grouping the wild rice accessions suggested wide divergence among the genotypes and could be utilized for the future rice genomic studies especially for development of stress tolerant rice varieties. The results suggest that the SSR markers are effective for assessing the genetic diversity of wild rice and its related species.

1. Introduction

Rice (*Oryza sativa* L.) is one of the world's most significant cereal crops, serving as a staple food for more than half of the global population including Bangladesh. In the context of climate change, abiotic stress and emergence of new strains, races or biotypes of biotic factors are endangering food security through yield loss of rice crop. Wild rice species serve as rich source of useful genes (Song et al., 2005) for biotic and abiotic stresses. *O. rufipogon* Griff. is a perennial species, which is widely distributed from southern part of China through south and south-east Asia down to Papua New Guinea and northern Australia (Vaughan, 1994), is a progenitor of Asian cultivated rice (Khush, 1997). As an ancestor of cultivated rice, wild species docks valuable genes for resistance to blast (Ram et al., 2007); brown plant hopper (Rongbai et al., 2001) and grassy stunt virus (Khush et al., 1977). Improved Sambha Mahsuri and improved Pusa Basmati1 were released in India introgressing Xa21 gene for bacterial blight (BB) resistance from *O. longistaminata*. Similarly, modern rice varieties BRRI dhan55, BRRI dhan87, BRRI dhan89 and BRRI dhan96 were developed and released in Bangladesh by hybridizing with *Oryza rufipogon* (BRRI, 2025). Wild rice *O. officinalis* contains the valuable genes for early morning flowering (EMF) trait to mitigate high temperature-induced sterility at anthesis (Ishimaru et al., 2010). Moreover, *O. minuta*, a tetraploid wild relative of cultivated rice, shows the potential resistance against blast, bacterial blight, white backed plant hopper (WBPH) and brown plant hopper (BPH). Again, various resistance genes have been transferred effectively to cultivated rice from

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O. minuta (Rahman et al., 2009). It is well recognized that wild rice species carries considerably higher genetic diversity than the cultivated rice (Sun et al., 2001).

Species with greater genetic diversity offer more variations to choose for the most appropriate alleles of a given trait. Species that have lesser genetic variation are at risk of extinction. The genetic diversity within the crop species essentially determines yield and a number of other economically advantageous traits in that crop species. The cultivated rice varieties available are the end product of human selection from the actual and available genetic diversity in the various wild types. Modern breeding programs have led to developed varieties that are more uniform, stable, and improved for the controlled and limited environments of traditional fields. As a result, the crop has become more susceptible to biotic and abiotic environmental stresses. However, natural populations of wild rice species are rapidly declining due to habitat loss, land-use changes, and climate impacts (Song et al., 2005; Gao, 2004), suggesting the urgency of conservation and characterization.

Molecular marker analysis is one of the most useful tools for evaluating the genetic variation of common wild rice germplasm (Liu et al., 2015; Wang et al., 2008; Zhou et al., 2003; Gao, 2004). With the initiation of PCR based molecular marker technology, SSR markers have been used for their high reproducibility, simplicity, easy scoring ability, reliability, co-dominant, multi-allelic nature and wide distribution across the genome (Siddique et al., 2014; Siddique et al., 2017; Islam et al., 2019; Islam et al., 2020; Vabna et al., 2021; Khalequzzaman et al., 2022; Siddique et al., 2023; Alkasim et al., 2024; Islam et al.,2025).

Bangladesh Rice Research Institute (BRRI) conserves more than 9000 rice germplasm accessions, including 90 wild rice and related species maintained under ex situ conservation (Siddique et al., 2025). Despite their importance, the genetic diversity and population structure of these wild rice accessions in Bangladesh have not been previously characterized. Therefore, the present study aimed to investigate the genetic diversity of wild rice using SSR markers and to analyze population structure using a model-based approach.

2. Materials and methods

2.1. Rice materials

A total 77 wild rice germplasm maintained in an ex-situ conservation in the net house under Genetic Resources and Seed Division (GRSD) of Bangladesh Rice Research Institute (BRRI) (Anonymous, 2025) were used in this study (Table 1).

Table 1
Name and origin of 77 wild rice and relatives.

Sl. No.	Species	Code Name	Origin/Source	Sl. No.	Species	Code Name	Origin/Source
1	*Oryza alta*	WR1	IRRI	40	*Oryza rufipogon*	WR40	Gauranadi, Barishal
2	*Oryza alta*	WR2	IRRI	41	*Oryza officinalis*	WR41	Jhalokhati
3	*Oryza alta*	WR3	IRRI	42	Unknown	WR42	Jhalokhati
4	*Oryza alta*	WR4	IRRI	43	*Oryza rufipogon*	WR43	Shibaloy, Manikganj
5	*Oryza latifolia*	WR5	IRRI	44	*Oryza rufipogon*	WR44	Rangpur Sadar
6	*Oryza latifolia*	WR6	IRRI	45	*Oryza rufipogon*	WR45	Chitalmari, Bagerhat
7	*Oryza granular*	WR7	IRRI	46	*Oryza rufipogon*	WR46	Betagi, Barguna
8	*Oryza longistaminata*	WR8	IRRI	47	*Oryza rufipogon*	WR47	Madhupur, Tangail
9	*Oryza longistaminata*	WR9	IRRI	48	*Oryza rufipogon*	WR48	Cumilla Sadar
10	*Oryza minuta*	WR10	IRRI	49	*Oryza rufipogon*	WR49	Gazipur Sadar
11	*Oryza officinalis*	WR11	Sonagazi, Feni	50	*Oryza rufipogon*	WR50	Wazirpur, Barishal
12	*Oryza officinalis*	WR12	Betagi, Barguna	51	*Oryza rufipogon*	WR51	Shibaloy, Manikganj
13	*Oryza punctata*	WR13	IRRI	52	*Oryza rufipogon*	WR52	Fakirhat, Bagerhat
14	*Oryza rufipogon*	WR14	IRRI	53	*Oryza rufipogon*	WR53	Madhupur, Tangail
15	*Oryza rufipogon*	WR15	IRRI	54	*Oryza rufipogon*	WR54	Domar, Nilphamari
16	*Oryza rufipogon*	WR16	IRRI	55	*Oryza rufipogon*	WR55	Habiganj Sadar
17	*Oryza rufipogon*	WR17	IRRI	56	*Oryza rufipogon*	WR56	Cumilla Sadar
18	*Oryza rufipogon*	WR18	IRRI	57	*Oryza rufipogon*	WR57	Barguna Sadar
19	*Oryza rufipogon*	WR19	IRRI	58	*Oryza rufipogon*	WR58	Shibaloy, Manikganj
20	*Oryza rufipogon*	WR20	IRRI	59	*Oryza rufipogon*	WR59	Domar, Nilphamari
21	*Oryza rufipogon*	WR21	IRRI	60	Unknown	WR60	Gazipur Sadar
22	*Oryza rufipogon*	WR22	IRRI	61	*Oryza rufipogon*	WR61	Habiganj Sadar
23	*Oryza rufipogon*	WR23	IRRI	62	*Oryza rufipogon*	WR62	Saghata, Gaibandha
24	*Oryza rufipogon*	WR24	IRRI	63	*Porteresia coarctata*	WR63	Batiaghata, Khulna
25	*Oryza rufipogon*	WR25	IRRI	64	*Oryza rufipogon*	WR64	Gauranadi, Barishal
26	*Oryza rufipogon*	WR26	IRRI	65	*Oryza rufipogon*	WR65	Betagi, Barguna
27	*Oryza rufipogon*	WR27	IRRI	66	*Oryza rufipogon*	WR66	Madhupur, Tangail
28	*Oryza rufipogon*	WR28	IRRI	67	*Oryza rufipogon*	WR67	Fakirhat, Bagerhat
29	*Oryza rufipogon*	WR29	IRRI	68	*Oryza rufipogon*	WR68	Wazirpur, Barishal
30	*Oryza rufipogon*	WR30	IRRI	69	*Oryza rufipogon*	WR69	Chitalmari, Bagerhat
31	*Oryza rufipogon*	WR31	IRRI	70	*Oryza rufipogon*	WR70	Shibaloy, Manikganj
32	*Porteresia coarctata*	WR32	Shyamnagar, Shatkhira	71	*Oryza rufipogon*	WR71	Madhupur, Tangail
33	*Oryza rufipogon*	WR33	Wazirpur, Barishal	72	*Oryza rufipogon*	WR72	Rangpur Sadar
34	*Oryza rufipogon*	WR34	Betagi, Barguna	73	*Oryza rufipogon*	WR73	Domar, Nilphamari
35	*Oryza rufipogon*	WR35	Mollahat, Bagerhat	74	*Oryza rufipogon*	WR74	Cumilla Sadar
36	*Oryza rufipogon*	WR36	Madhupur, Tangail	75	*Oryza rufipogon*	WR75	Habiganj Sadar
37	*Oryza rufipogon*	WR37	Habiganj Sadar	76	*Oryza rufipogon*	WR76	Batiaghata, Khulna
38	*Oryza rufipogon*	WR38	Domar, Nilphamari	77	*Oryza rufipogon*	WR77	Fakirhat, Bagerhat
39	*Oryza rufipogon*	WR39	Saghata, Gaibandha				

WR = wild rice, IRRI = International Rice Research Institute, Unknown = Species not identified yet

2.2. SSR markers

Forty-two well distributed SSRs were used for diversity analysis. The chromosomal position (cM) and repeat motifs for these markers were retrieved from rice genome database (http://www.gramene.org). Marker position and motif of 42 SSRs are presented in Table 2.

2.3. Genomic DNA isolation and PCR amplification

DNA was extracted from the collected young leaves following the quick DNA extraction protocol of Ferdous et al. (2012). PCR analysis was performed in 10 µL reaction sample containing 3 µL of DNA template, 4.5 µL of Go Taq G2 Green Master Mix (Promega), 1.5 µL of Nuclease-Free Water, 0.5 µL each of 10 µM forward and reverse primers using a GeneAtlas G (Astec, Japan) 96-well thermal cycler. The mixture was overlaid with 10 µL of mineral oil to prevent evaporation. After initial denaturation for five minutes at 94°C, each cycle comprised 30 sec denaturation at 95°C, 30 sec annealing at 55°C, and 25 sec extensions with a final extension for 5 min at 72°C at the end of 32 cycles.

2.4. Electrophoresis and visualization of amplified products

The PCR products were mixed with bromophenol blue gel loading dye and were analyzed by electrophoresis on 8% polyacrylamide gel using a mini vertical polyacrylamide gels electrophoresis machine (CBS Scientific Co. Inc., CA, USA). 2.5 µL of amplification products were resolved by running gel in 0.5X TBE buffer for 1.5-2.5 hrs depending upon the allele size at around 100 volts and 500 mA current. The gels were stained in 5 µL SYBR Safe DNA gel stain (10,000X concentration in DMSO, USA) with 200 mL 0.5X TBE buffer for 15 min and exposed to UV light using a molecular imager gel documentation unit (XR System, Uvitec Cambridge, France) for visualization.

2.5. Allele scoring and diversity data analysis

The band size for each marker was measured by Alpha Ease FC 4.0 software. The summary statistics of the marker data such as the average number of alleles per locus, major allele frequency, gene diversity and polymorphism information content (PIC) were done by using Power Marker V3.25 (Liu and Muse, 2005). For the unrooted phylogenetic tree, genetic distance was calculated using the "C.S. Chord 1967" distance measure (Cavalli-Sforza and Edwards, 1967) followed by phylogeny reconstruction using neighbour joining as implemented in MEGA 5.1 software (Tamura et al., 2011). The allele frequency data were exported in binary format (allele presence = "1" and allele absence = "0") for analysis with NTSYS-pc version 2.2 (Rohlf, 2002). A similarity matrix was calculated with the Sim Qual subprogram using the Dice coefficient, followed by cluster analysis with the SAHN sub-program using the UPGMA (unweighted pair group method using the arithmetic mean) clustering method as implemented in NTSYS-pc. Principal coordinate analysis (PCoA) analysis is a form of multivariate analysis that forms groupings of germplasm based on either similarity co-efficient or variance-covariance values. It provides further information on the differentiation of major groups (Venkatesan and Bhat, 2015). Hence, the similarity matrix was also used PCoA with the Center, Eigen, Output, and MXPlot sub-programs in NTSYS-pc.

2.6. Population structure analysis

Population structure was examined using the Bayesian model-based approach implemented in STRUCTURE V2.3.4 (Pritchard et al., 2000). The number of subpopulations was classified based on the true K value. The number of clusters (K) ranged from 1 to 10. The analysis was performed using five replicate runs per K value, a burn-in period length of 5000, a run length of 50000, and the admixture model was followed. 'Structure harvester' program (http://taylor0.biology.ucla.edu) was used to determine the final K value (K = 3 was optimum for this analysis) based on both the LnP(D) and Evanno's Δ K (Evanno et al., 2005).

3. Results

3.1. SSR diversity of wild rice and relatives

In this research, genetic diversity of 77 wild rice and relatives were analyzed using 42 simple sequence repeat (SSR) markers located on all 12 chromosomes. The basic statistics of the 42 SSR markers are listed in Table 2. A total of 200 alleles were detected, which varied from 2 (RM454) to 9 (RM154), averaging 4.76 alleles per locus. The major alleles were sized between 66 bp (RM413) and 270 bp (RM496) and the frequency of the major alleles ranged from 33.00% to 94.00%. On average, 66.43% of the 77 wild rice and relatives had at least one major allele common across the loci. Gene diversity ranged between 0.12 (RM237) and 0.79 (RM154), with an average of 0.48, while PIC values ranged from 0.12 (RM237) to 0.76 (RM154), and averaging 0.44. Because of higher PIC value (0.76) and gene diversity (0.79), RM154 locus was classified as the best SSR marker for determining the 77 wild rice germplasm. DNA profile of the 77 wild rice and relatives is shown with an SSR marker RM20 in Fig. 1.

A total of 19 distinct alleles were amplified from 16 SSR markers (Table 3) with one to two unique alleles per locus. Of the 16 SSR markers, 13 SSR markers amplified only one unique allele, while three markers amplified two unique alleles across 77 wild rice accessions. Notably, four SSR markers, RM334 (chromosome 5, 155 bp), RM413 (chromosome 5, 70 bp), RM178 (chromosome 05, 122 bp), and RM237 (chromosome 01, 117 bp), amplified specific alleles only for WR60 (Unknown). Furthermore, there were two unique alleles amplified specific to WR4 (RM527, RM447), WR16 (RM334, RM338), WR21 (RM154, RM161), WR32 (RM118, RM507), and WR42 (RM224, RM320). The 232bp allele amplified by the SSR marker RM527 was specific to the wild rice WR4. Besides, two unique alleles 234bp and 185 bp were amplified by the marker RM20 from wild rice genotype WR25 and WR40, respectively. Likely, the marker RM334 amplified unique alleles of 208 bp and 155 bp in WR16 and WR60, respectively. The marker RM19 amplified a unique allele of 200 bp in WR41. RM282 also amplified a unique allele of 109bp in WR12. Likewise, the marker RM507 amplified unique alleles of 154 bp and 160 bp in WR32 and WR63 wild rice, respectively.

Table 2
Allele number, size and frequency, gene diversity and polymorphism information content of 42 SSR markers across 77 wild rice and relatives.

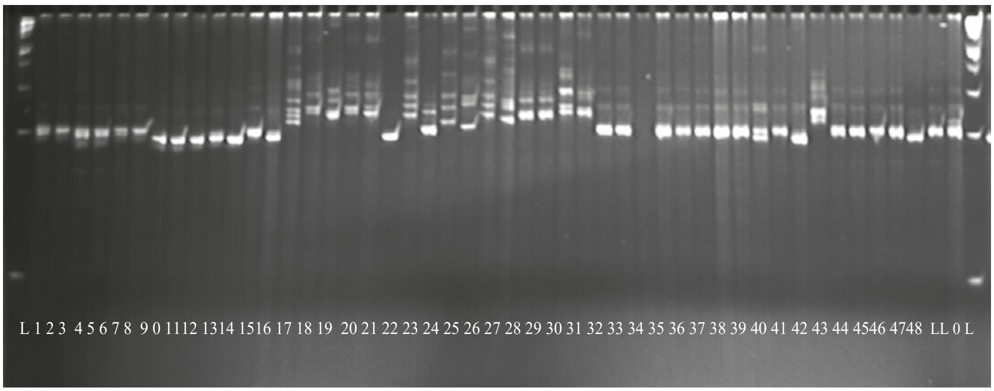
Marker	Chro. No.	Position (cM)	Motif*	No. of Allele	Size range (bp)	Size (bp)	Freq (%)	Gene diversity	PIC
RM20	12	0	(ATT)14	6	182-240	182	60.00	0.59	0.54
RM224	11	120.1	(AAG)8(AG)13	6	111-142	142	42.00	0.72	0.68
RM320	7	62.4	(AT)11GTATGT)13	4	122-184	184	78.00	0.37	0.33
RM334	5	141.8	(CTT)20	7	130-208	208	74.00	0.43	0.40
RM413	5	26.7	(AG)11	6	66-100	66	64.00	0.56	0.53
RM496	10	113	(TC)14	5	219-270	270	68.00	0.50	0.46
RM527	6	61.2	(GA)17	4	202-232	232	71.00	0.45	0.38
RM151	1	36.2	(TA)23	4	170-225	225	83.00	0.30	0.29
RM487	3	127.9	(AC)10	3	180-186	180	87.00	0.23	0.21
RM567	4	153.6	(GA)21	3	240-260	260	79.00	0.34	0.30
RM14643	3	53.1	(GA)n	4	97-136	136	53.00	0.63	0.57
RM222	10	11.3	(CT)18	4	85-238	238	51.00	0.65	0.60
RM338	3	108.4	(CTT)6	3	179-190	190	91.00	0.17	0.16
RM412	6	142.4	(GA)22	5	178-202	202	55.00	0.60	0.53
RM432	7	43.5	(CATC)9	3	178-225	178	86.00	0.25	0.23
RM442	3	224.2	(AAG)10	5	241-266	266	77.00	0.40	0.38
RM6	2	154.7	(AG)16	3	155-214	155	62.00	0.54	0.48
RM11	7	47	(GA)17	5	118-140	140	77.00	0.40	0.38
RM19	12	20.9	(ATC)10	6	200-260	200	66.00	0.55	0.52
RM44	8	60.9	(GA)16	3	96-114	96	78.00	0.36	0.33
RM105	9	32.1	(CCT)6	4	105-148	148	55.00	0.61	0.56
RM118	7	96.9	(GA)8	6	156-178	156	66.00	0.52	0.48
RM125	7	24.8	(GCT)8	4	114-128	128	65.00	0.50	0.43
RM134	7	-	(CCA)7	5	80-96	96	51.00	0.62	0.55
RM154	2	4.8	(GA)21	9	138-220	220	33.00	0.79	0.76
RM161	5	96.9	(AG)20	7	120-196	196	44.00	0.69	0.65
RM165	1	-	(CT)13	5	164-195	185	43.00	0.67	0.61
RM178	5	118.8	(GA)5(AG)8	5	90-122	122	48.00	0.65	0.59
RM215	9	99.4	(CT)16	4	135-150	148	44.00	0.61	0.53
RM282	3	100.6	(GA)15	7	100-142	142	56.00	0.63	0.60
RM284	8	83.7	(GA)8	4	80-92	92	83.00	0.30	0.28
RM316	9	1.8	(GT)8(TG)9(TTTG)4 (TG)4	8	175-235	175	66.00	0.54	0.52
RM408	8	1.1	(CT)13	4	111-125	125	70.00	0.46	0.40
RM447	8	124.6	(CTT)8	7	79-132	132	69.00	0.49	0.46
RM454	6	99.3	(GCT)8	2	267-290	267	73.00	0.40	0.32
RM507	5	0	(AAGA)7	5	154-253	253	75.00	0.40	0.37
RM515	8	80.5	(GA)11	6	204-230	204	52.00	0.64	0.59
RM566	9	47.7	(AG)15	3	230-245	245	82.00	0.31	0.28
RM18	7	90.4	(GA)4AA(GA)(AG)16	6	139-178	139	52.00	0.66	0.62
RM237	1	115.2	(CT)18	3	117-132	132	94.00	0.12	0.12
RM133	6	0	(CT)8	4	215-228	228	92.00	0.15	0.14
RM26243	11	-	(CTG)8	3	172-220	220	75.00	0.39	0.34
Total				200		7503	2790.00	20.17	18.49
Minimum				2		66	33.00	0.12	0.12
Mean				4.76		178.64	66.43	0.48	0.44
Maximum				9		270	94.00	0.79	0.76

Table 3
Genotype-specific alleles identified for 11 wild rice and relatives.

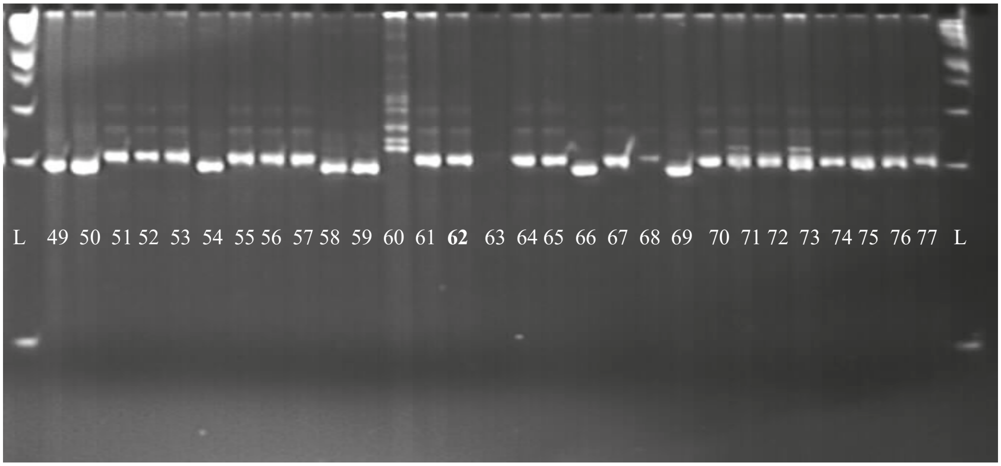
Sl. no.	Locus	Chromosome	Unique Allele	Size (bp)	Code no. of wild rice and relatives
1	RM20	12	1	234	WR25
2	RM20	12	1	185	WR40
3	RM224	11	1	111	WR42
4	RM320	7	1	184	WR42
5	RM334	5	1	208	WR16
6	RM334	5	1	155	WR60
7	RM413	5	1	70	WR60
8	RM527	6	1	232	WR4
9	RM338	3	1	179	WR16
10	RM19	12	1	200	WR41
11	RM118	7	1	178	WR32
12	RM154	2	1	138	WR21
13	RM161	5	1	132	WR21
14	RM178	5	1	122	WR60
15	RM282	3	1	109	WR12
16	RM447	8	1	94	WR4
17	RM507	5	1	154	WR32
18	RM507	5	1	160	WR63
19	RM237	1	1	117	WR60

200bp →

100bp →



Legend: 1.WR1, 2.WR2, 3.WR3, 4.WR4, 5.WR5, 6.WR6, 7.WR7, 8.WR8, 9.WR9, 10.WR10, 11.WR11, 12.WR12, 13.WR13, 14.WR14, 15.WR15, 16.WR16, 17.WR17, 18.WR18, 19.WR19, 20.WR20, 21.WR21, 22.WR22, 23.WR23, 24.WR24, 25.WR25, 26.WR26, 27.WR27, 28.WR28, 29.WR29, 30.WR30, 31.WR31, 32.WR32, 33.WR33, 34.WR34, 35.WR35, 36.WR36, 37.WR37, 38.WR38, 39.WR39, 40.WR40, 41.WR41, 42.WR42, 43.WR43, 44.WR44, 45.WR45, 46.WR46, 47.WR47, 48.WR48.



Legend: 49.WR49, 50.WR50, 51.WR51, 52.WR52, 53.WR53, 54.WR54, 55.WR55, 56.WR56, 57.WR57, 58.WR58, 59.WR59, 60.WR60, 61.WR61, 62.WR62, 63.WR63, 64.WR64, 65.WR65, 66.WR66, 67.WR67, 68.WR68, 69.WR69, 70.WR70, 71.WR71, 72.WR72, 73.WR73, 74.WR74, 75.WR75, 76.WR76, 77.WR77.

Fig. 1. DNA profile of 77 wild rice and relatives with RM20.

3.2. UPGMA cluster analysis

The UPGMA cluster analysis categorized 77 wild rice and relatives into five separate clusters at a coefficient of 0.49. The distance coefficient varied from 0.27 to 1.00 as illustrated in Fig. 2. Cluster I contained 58 wild rice and relatives, while clusters II contained 14, cluster III and IV each contained two and cluster V contained one wild rice germplasm (Table 4). Interestingly, *Oryza rufipogon* accession, WR36 collected from Tangail (central part of Bangladesh) and *Oryza rufipogon* accession, WR57 collected from Barguna district (southern region) were grouped into cluster III, while Cluster IV had two other wild rice accessions - WR24 which was collected from IRRI and WR60 from Gazipur district. Cluster V contained only one wild rice (WR14, *O. rufipogon*) accession, which was also obtained from IRRI.

Most of the wild rice accessions in Cluster I were collected from IRRI and from various locations in Bangladesh. The wild rice species classified in the cluster I were *Oryza alta* (04), *O. latifolia* (01), *O. officinalis* (02), *O. rufipogon* (49), *Porteresia coarctata* (02). Among these, two accessions of *Porteresia coarctata*, WR32 were collected from Shyamnagar, Satkhira, and WR63 were collected from Batiaghata, Khulna (South-west coastal region) of Bangladesh. Cluster II contained six different wild rice species, *Oryza latifolia, O. granular, O longistaminata, O. minuta, O. punctata* and *O. rufipogon*, all were collected from IRRI. Cluster II has the highest species diversity than all other four clusters.

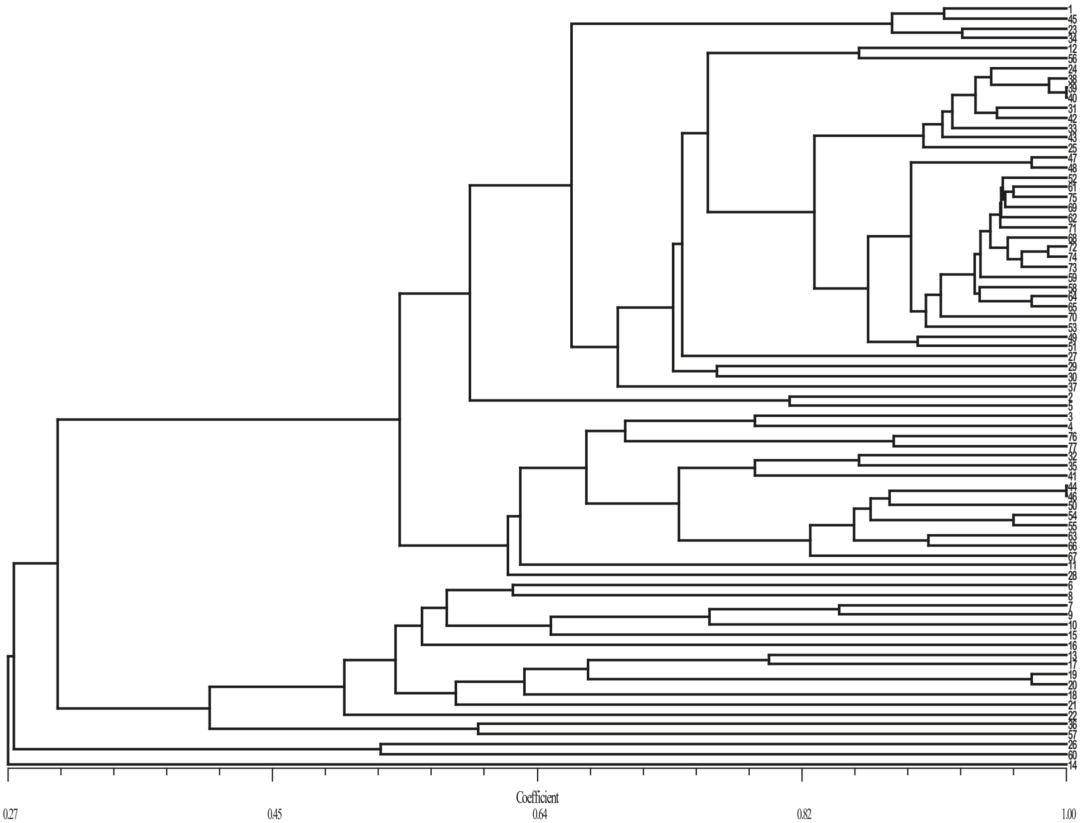


Fig. 2. Cluster analysis of 77 wild rice and relatives based on SSR markers polymorphism.

Table 4
Cluster group based on 42 SSR markers.

Cluster	Number of wild rice and relatives	Code name of wild rice and relatives	Frequency (%)
I	58	WR1, WR2, WR3, WR4, WR5, WR11, WR12, WR23, WR25, WR26, WR27, WR28, WR29, WR30, WR31, WR32, WR33, WR34, WR35, WR37, WR38, WR39, WR40, WR41, WR42, WR43, WR44, WR45, WR46, WR47, WR48, WR49, WR50, WR51, WR52, WR53, WR54, WR55, WR56, WR58, WR59, WR61, WR62, WR63, WR64, WR65,WR66, WR67, WR68, WR69, WR70,WR71, WR72, WR73, WR74, WR75, WR76, WR77	75.32
II	14	WR6, WR7, WR8, WR9, WR10, WR13,WR15, WR16, WR17, WR18, WR19, WR20, WR21, WR22	18.18
III	2	WR57, WR36	2.6
IV	2	WR60, WR24	2.6
V	1	WR14	1.3

3.3. Genetic distance-based analysis

The unrooted neighbor-joining tree of genetic distance-based results showed that the 77 wild rice and relatives were clustered into main three clusters (Fig. 3). The 77 wild rice and relatives were also clustered into several sub-clusters. Cluster I contained the largest number of wild rice (74) followed by II (2) and III (1), which contained the lowest number of wild rice accessions.

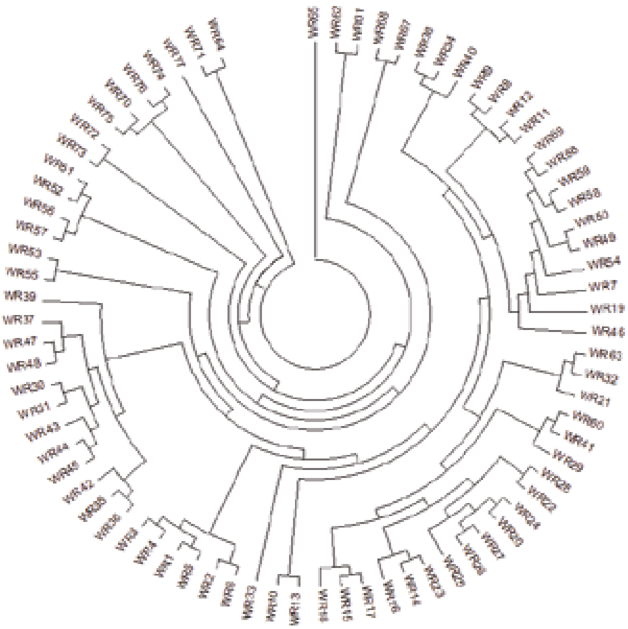


Fig. 3. An unrooted neighbor-joining tree showing the genetic relationships among 77 wild rice and relatives.

3.4. Population structure analysis

A Bayesian STRUCTURE based method was used to investigate the population structure of the 77 wild rice and relatives. The structure analysis was carried out with K set at 1 to 10 with 5 iterations which demonstrated a maximum log likelihood of K = 3 (Fig. 4) which was indicative of three distinct groups representing three main clusters, namely, GI (red color), GII (green color) and GIII (blue color) (Fig. 5). The first group consisted of 35 genotypes (45.45%), the second group consisted of 23 genotypes (29.87%), and the third group consisted of 19 genotypes (24.68%). Overall, 24 (31.16%) of wild rice exhibited evidence of admixture when K = 3.

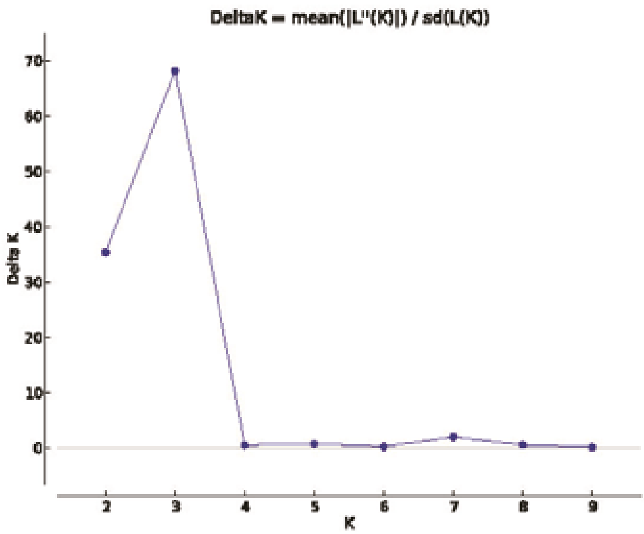


Fig. 4. STRUCTURE estimation of the number of groups for the K values ranging from 1 to 10, by delta K values.

The PCoA analysis clearly segregated wild rice and relatives based on their place of origin (Figs. 6 and 7). Wild rice was dispersed throughout the PCoA plot. The figures of PCoA provided two and three-dimensional representations of the spatial distributions of wild rice according to their place of origin/source. The wild rices namely *Oryza rufipogon* (WR69), *Oryza rufipogon* (WR59), *Oryza rufipogon* (WR66), *Oryza longistaminata* (WR8), *Oryza rufipogon* (WR19), *Oryza rufipogon* (WR18), *Oryza rufipogon* (WR38), *Oryza rufipogon* (WR28), *Oryza rufipogon* (WR21), *Porteresia coarctata* (WR32) and *Porteresia coarctata* (WR63) were found far away from the centroid of the cluster and the remaining wild rices were found more or less around the centroid (Figs. 6 and 7). The farther the distance of germplasm from the centroid, the greater is the genetic diversity and vice-versa.

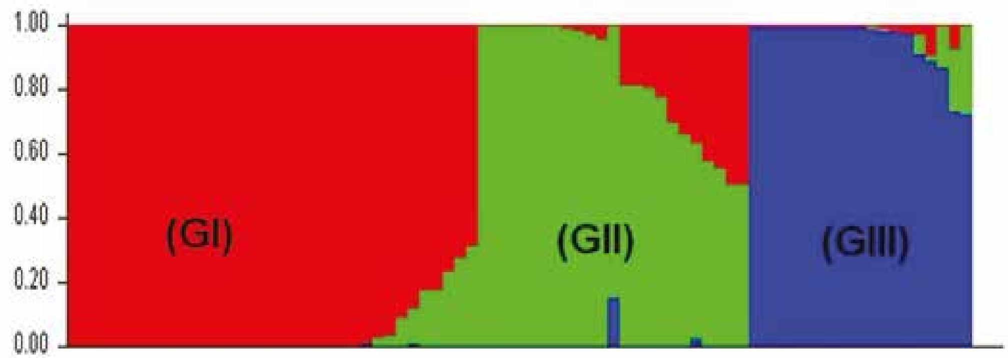


Fig. 5. Assignment of 77 wild rice and relatives to three groups (GI, GII and GIII) using STRUCTURE 2.3.4 software.

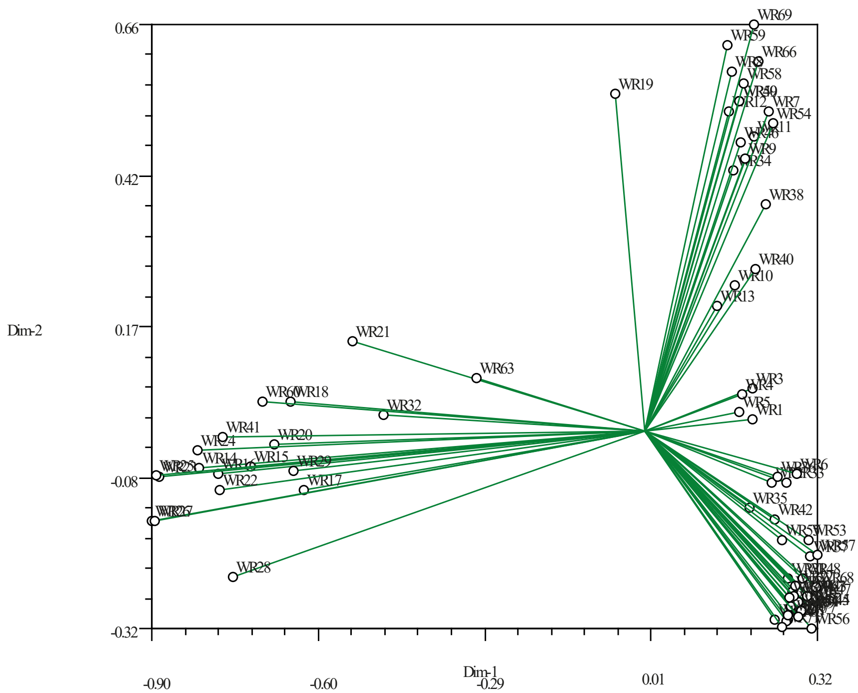


Fig. 6. Two-dimensional view of principal coordinate analysis (PCoA) with 42 SSR markers over 77 wild rice and relatives.

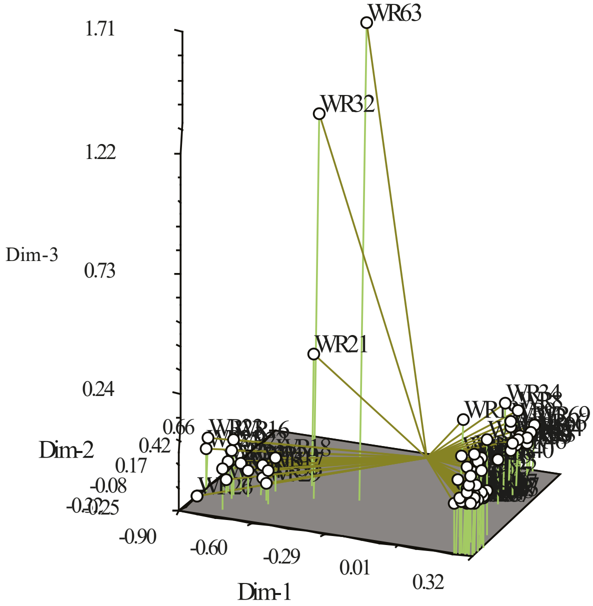


Fig. 7. Three-dimensional view of principal coordinate analysis (PCoA) with 42 SSR markers over 77 wild rice and relatives.

4. Discussion

Genetic divergence is important for the survival and adaptation of a species. Adapting to a changing environment often requires multiple resilience mechanisms in organism morphology to adapt and survive in extreme conditions. The improvement of rice varieties necessitates the detection of both highly diverse wild rice germplasm and highly polymorphic molecular markers that can be effectively used to map genes/QTLs for traits of economic importance followed by their application in molecular breeding. This study was undertaken to determine the genetic diversity of wild rice accessions collected from Bangladesh and IRRI Philippines.

Molecular markers are better suited for identification of diverse germplasm than conventional methods (Thompson et al., 1998). This study used SSR markers data to analyze genetic diversity and to determine the level of genetic diversity among WR germplasms studied. The PIC value reflects the allelic variation, and frequency exists in the studied germplasm. In this study, the PIC ranged from 0.12 to 0.76, with an average of 0.44, which is consistent with previous PICs ranging from 0.40 to 0.88, averaging 0.71 (Prathepha., 2012) and PICs of 0.28 to 0.72, averaging 0.52 (Singh et al., 2016) which were both considerably higher than this study. Eighteen SSR markers exhibited PIC values above 0.5 with the highest PIC value (0.76) by RM154 and the least by RM237 (0.12), suggesting the highest polymorphism with RM154 and the least polymorphism with R237. Thus, high values of PIC are assumed to be representative of more informative or robustness of the markers (Islam et al., 2025) and lower values of PIC, generally represent a collection of germplasm based on a similar background or closely related types; high values indicate a greater diversity of germplasm (Islam et al., 2018a). The above results indicated that the 18 SSR markers with average PIC value of 0.44 can be a panel marker set for discriminating WR accessions as well as for detection of the potential duplicates among the studied WR accession and RM154 could be used reliably to distinguish wild germplasm accessions of rice.

Out of 68 markers evaluated in this study, 19 unique allelic profiles of 16 SSR marker were found in 11 wild rice accessions. These 19 unique alleles can be useful in accurately identifying these WR genotypes. The identification and use of unique alleles could have significant value in breeding programs (Behera et al., 2012; Thudi and Fakrudin., 2011). In addition, with a varietal improvement breeding program, germplasm with a higher number of unique alleles might represent a potential bank of unique and novel alleles (Singh et al., 2013). Unique alleles were also found in cultivated and wild rice (Wong et al., 2009 and Giarrocco et al., 2007), and the utility of unique alleles were also discussed for DNA fingerprinting by Nagaraju et al. (2002), Jain et al. (2004); Shivapriya and Hittalmani (2006); Das et al. (2013).

The dendrogram constructed based on hierarchical clustering categorized 77 wild rice and relatives' accessions into five main groups (Fig. 2), in which majority of the *Oryza rufipogon* germplasm accessions were grouped into cluster I. This implied shared ancestry of these accessions; however, cluster II demonstrated diversity even among the wild rice and relatives.

STRUCTURE analysis with the greatest log likelihood at K=3 revealed three major sub-groups (GI, GII and GIII) among the studied wild rice accessions. A similar structure of three sub-groups was noted previously by Roy et al. (2015) in a collection of 107 aromatic rice landraces in India, and three groups were also classified by Islam et al. (2018b) in indica aromatic rice germplasm in Bangladesh. Population structure analyses of various rice diversity panels have reported differing numbers of sub-groups, ranged from 2 to 8 (Garris et al., 2005; Liakat-Ali et al., 2011; Das et al., 2013; Huang et al., 2015; Islam et al., 2021).

STRUCTURE analysis at K = 3 revealed three major genetic groups (GI, GII and GIII), with a substantial proportion of accessions displaying admixed ancestry (Fig. 5). Overall, 24 out of 77 accessions (31.16%) showed admixture (membership coefficient $Q < 0.80$), indicating historical or ongoing gene flow among wild rice populations. The observed admixture patterns correspond well with the geographic distribution of wild rice accessions across Bangladesh and IRRI collections. Many admixed accessions in GII (approximately 33–38% of accessions) and GIII (where ~25–30% of accessions) originated from ecologically heterogeneous and geographically connected regions, such as the central zone (Gazipur, Tangail), southern coastal belt (Barguna, Bagerhat, Khulna), and floodplain ecosystems, which are characterized by seasonal flooding, tidal influence, and frequent habitat disturbance; indicating weaker genetic differentiation in these groups.

In particular, coastal and lowland wild rice accessions (e.g., from Barguna, Khulna and Bagerhat) showed mixed ancestry between GI and GIII, suggesting secondary contact between genetically differentiated populations adapted to contrasting ecological niches. Similar geographic patterns of admixture have been reported in *Oryza rufipogon* populations from China and Southeast Asia, where river networks, monsoon-driven flooding, and human-mediated landscape changes enhanced gene flow among populations (Gao., 2004; Wang et al., 2008; Liu et al., 2015).

According to the results of this study, 14.28% of wild rice (WR69, WR59, WR66, WR8, WR19, WR18, WR38, WR28, WR21, WR32, WR63) clustered far away from the centroid of the cluster. The remaining 85.72 % of the wild rice accessions clustered around the centroid. Germplasm which clustered together are supposed to have high genetic similarity, whereas those that are found far away from each other are assumed to be divergent (Siddique et al., 2016a and 2016b; Khalequzzaman et al., 2017; Khalequzzaman et al., 2018; Islam et al., 2023; Siddique et al., 2023).

5. Conclusion

The creation and maintenance of genetic diversity in breeding germplasm and genetic stocks are essential to accelerate the response to selection. Wild rice and related taxa are considered as a potential source of resilient genes for genetic improvement of cultivated rice varieties. Genetic studies of wild rice are required to provide information for their proper utilization by hybridization, management and conservation programs. The present research investigated the genetic diversity and population structure of wild rice obtained from the IRRI and BRRI Genebank. SSR-based analysis revealed a high level of genetic diversity among the studied wild rice accessions and their relatives. The divergent genotypes (WR69, WR59, WR66, WR8, WR19, WR18, WR38, WR28, WR21, WR32, WR63) identified in this study can be used in the future rice improvement programs. The findings indicate that SSR markers are effective tools to estimate genetic diversity in wild rice. Owing to their enormous variability, these wild rice germplasms offer strong potential for allele mining and advanced rice breeding. It can be concluded that wild rice germplasm should be conserved both ex-situ and in-situ for future use against abiotic and biotic stresses.

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Declaration of interests

The authors declare that they have no conflicts of interest.

References

Alkasim, S. M., Ibrahim, M. I., Hafsat, S. M., Tswanya, M. N., Hasanuzzaman, M., Arifuzzaman, M., Islam, M. Z., Suleiman, H., & Abubakar, S. (2024). Molecular variation and genetic divergence in T. Aman rice genotypes using SSR markers. Malaysian Journal of Sustainable Agriculture, 8(2), 32–39. https://doi.org/10.26480/mjsa.02.2024.32.39

Anonymous. (2025). BRRI genebank: A very short introduction (Leaflet). Genetic Resources and Seed Division, Bangladesh Rice Research Institute, Gazipur.

Behera, L., Patra, B. C., Sahu, R. K., Nanda, A., Sahu, S. C., & Patnaik, A. (2012). Assessment of genetic diversity in medicinal rices using microsatellite markers. Australian Journal of Crop Science, 6, 2012.

Bangladesh Rice Research Institute (BRRI). (2025). Modern rice cultivation (25th ed., p. 128). BRRI.

Cavalli-Sforza, L L and A W F Edwards. 1967. Phylogenetic analysis. Models and estimation procedures. American Journal of Human Genetics, 19(3): 233–257.

Das, B., Sengupta, S., Parida, S. K., Roy, B., Ghosh, M., & Prasad, M. (2013). Genetic diversity and population structure of rice landraces from Eastern and North Eastern states of India. BMC Genetics, 14, 71. http://www.biomedcentral.com/1471-2156/14/71

Evanno, G., Regnaut, S., & Goudet, J. (2005). Detecting the number of clusters of individuals using the software STRUCTURE: A simulation study. Molecular Ecology, 14, 2611–2620. https://doi.org/10.1111/j.1365-294X.2005.02553.x

Ferdous, J., Hanafi, M. M., Rafii, M. Y., & Muhammad, K. (2012). A quick DNA extraction protocol without liquid nitrogen at ambient temperature. African Journal of Biotechnology, 11(27), 6956–6964. https://doi.org/10.5897/AJB11.3283

Gao, L. Z. (2004). Population structure and conservation genetics of wild rice *Oryza rufipogon* (Poaceae): A region-wide perspective from microsatellite variation. Molecular Ecology, 13, 1009–1024.

Garris, A. J., Tai, T. H., Coburn, J., Kresovich, S., & McCouch, S. (2005). Genetic structure and diversity in rice (*Oryza sativa* L.). Genetics, 169, 1631–1638.

Giarrocco, L., Marassi, M., & Salerno, G. (2007). Assessment of the genetic diversity in Argentine rice cultivars with SSR markers. Crop Science, 47(2), 853–858.

Huang, M., Wu, Y., & Tao, X. (2015). Genetic diversity of main inbred Indica rice varieties applied in Guangdong Province as revealed by molecular markers. Rice Science, 22(1), 1–8.

Ishimaru, T., Hirabayashi, H., Ida, M., Takai, T., San-Oh, Y. A., Yoshinaga, S., Ando, I., Ogawa, T., & Kondo, M. (2010). A genetic resource for early-morning flowering trait of wild rice Oryza officinalis to mitigate high temperature-induced spikelet sterility at anthesis. Annals of Botany, 106, 515–520.

Islam, M. Z., Siddique, M. A., Akter, N., Prince, M. F. R. K., Islam, M. R., Anisuzzaman, M., & Mian, M. A. K. (2019). Morpho-molecular divergence of restorer lines for hybrid rice (*Oryza sativa* L.) development. Cereal Research Communications, 47(3), 531–540.

Islam, M. Z., Arifuzzaman, M., Banik, S., Hossain, M. A., Ferdous, J., Khalequzzaman, M., et al. (2020). Mapping QTLs underpin nutrition components in aromatic rice germplasm. PLoS ONE, 15(6), e0234395. https://doi.org/10.1371/journal.pone.0234395

Islam, M. Z., Chakrabarty, T., Akter, N., Khalequzzaman, M., Prince, M. F. R. K., Pittendrigh, B. R., Tomita, M., & Ali, M. P. (2025). Genetic variability, correlation and path coefficient analysis of phenotypic traits and genetic diversity of Aman rice landraces (*Oryza sativa* L.). Scientific Reports, 15, 18606. https://doi.org/10.1038/s41598-025-03547-x

Islam, M. Z., Khalequzzaman, M., Prince, M. F. R. K., Siddique, M. A., Rashid, E. S. M. H., & Ahmed, M. S. U. (2018a). Diversity and population structure of red rice germplasm in Bangladesh. PLoS ONE, 13(5), e0196096. https://doi.org/10.1371/journal.pone.0196096

Islam, M. Z., Khalequzzaman, M., Bashar, M., Ivy, N. A., Mian, M. A. K., Pittendrigh, B. R., Haque, M. M., & Ali, M. P. (2018b). Variability assessment of aromatic rice germplasm by pheno-genomic traits and population structure analysis. Scientific Reports, 8, 9911. https://doi.org/10.1038/s41598-018-28001-z

Islam, M. Z., Khalequzzaman, M., Chakrabarty, T., Akter, N., Prince, M. F. R. K., Bhuiya, A., & Siddique, M. A. (2021). Genetic diversity and population structure of similarly named aromatic rice (*Oryza sativa* L.) landraces of Bangladesh. SAARC Journal of Agriculture, 19(2), 57–71. https://doi.org/10.3329/sja.v19i2.57826

Islam, M. Z., Siddique, M. A., Prince, M. F. R. K., Rashid, E. S. M. H., & Khalequzzaman, M. (2023). Molecular diversity analysis of some selected BRRI-developed rice varieties using SSR markers. SAARC Journal of Agriculture, 21(2), 1–14.

Jain, S., Jain, R. K., & McCouch, S. R. (2004). Genetic analysis of Indian aromatic and quality rice (*Oryza sativa* L.) germplasm using fluorescent microsatellite markers. Theoretical and Applied Genetics, 109(5), 965–977.

Khalequzzaman, M., Islam, M. Z., Prince, M. F. R. K., Rashid, E. S. M. H., & Siddique, M. A. (2022). Genetic diversity and population structure of Boro rice landraces of Bangladesh. Rice Research: Open Access, 10(6).

Khalequzzaman, M., Islam, M. Z., Siddique, M. A., Prince, M. F. R. K., Rashid, E. S. M. H., & Ahmed, M. S. (2017). Genetic diversity in Aus rice landraces of Bangladesh using SSR markers. Bangladesh Journal of Plant Breeding and Genetics, 30(1), 11–20.

Khalequzzaman, M., Prince, M. F. R. K., Islam, M. Z., Rashid, E. S. M. H., & Siddique, M. A. (2018). Microsatellite marker-based genetic diversity analysis of Aman rice (*Oryza sativa* L.) landraces. Bangladesh Journal of Plant Breeding and Genetics, 31(2), 1–11.

Khush, G. S., Ling, K. C., Aquino, R. C., & Aguiero, V. M. (1977). Breeding for resistance to grassy stunt in rice. In Proceedings of the 3rd International Congress of SABRAO (pp. 12–13). Canberra, Australia.

Khush, G. S. (1997). Origin, dispersal, cultivation and variation of rice. Plant Molecular Biology, 35, 25–34.

Liakat-Ali, M., McClung, A. M., Jia, M. H., Kimball, J. A., McCouch, S., & Eizenga, G. (2011). A rice diversity panel evaluated for genetic and agro-morphological diversity. Crop Science, 51, 2021–2035.

Liu, K., & Muse, S. V. (2005). PowerMarker: An integrated analysis environment for genetic marker analysis. Bioinformatics, 21, 2128–2129. https://doi.org/10.1093/bioinformatics/bti282

Liu, W., Shahid, M. Q., Bai, L., Lu, Z., Chen, Y., & Jiang, L. (2015). Evaluation of genetic diversity and development of a core collection of wild rice (Oryza rufipogon Griff.) populations in China. PLoS ONE, 10(12), e0145990. https://doi.org/10.1371/journal.pone.0145990

Nagaraju, J., Kathirvel, M., Ramesh, K. R., Siddiq, E. A., & Hasnain, S. E. (2002). Genetic analysis of traditional and evolved Basmati and non-Basmati rice varieties using fluorescence-based ISSR-PCR and SSR markers. Proceedings of the National Academy of Sciences of the United States of America, 99(9), 5836–5841.

Prathepha, P. (2012). Genetic diversity and population structure of wild rice, *Oryza rufipogon*, from Northeastern Thailand and Laos. Australian Journal of Crop Science, 6(4), 717–723.

Pritchard, J. K., Stephens, M., & Donnelly, P. (2000). Inference of population structure using multilocus genotype data. Genetics, 155, 945–959.

Rahman, M. L., Jiang, W., Chu, S. H., Qiao, Y., Ham, T. H., & Woo, M. O. (2009). High-resolution mapping of two rice brown planthopper resistance genes, Bph20(t) and Bph21(t), originating from *Oryza minuta*. Theoretical and Applied Genetics, 119(7), 1237–1246. https://doi.org/10.1007/s00122-009-1125-z

Ram, T., Majumder, N. D., Mishra, B., Ansari, M. M., & Padmavathi, G. (2007). Introgression of broad-spectrum blast resistance gene(s) into cultivated rice (*Oryza sativa* ssp. indica) from wild rice O. rufipogon. Current Science, 92, 225–228.

Rohlf, F. (2002). NTSYS-pc: Numerical taxonomy and multivariate analysis system (Version 2.2). Department of Ecology and Evolution, State University of New York, Stony Brook.

Rongbai, L., Xueyi, Q., Sumei, W., Pandey, M. P., Pathak, P. K., Fenguan, H., Qing, L., & Shanyu, L. (2001). Inheritance of resistance to brown plant hopper in an *Oryza rufipogon* (Griff.)-derived line in rice. Current Science, 80, 1421–1423.

Roy, S., Banerjee, A., Mawkhlieng, B., Misra, A. K., Pattanayak, A., Harish, G. D., Singh, S. K., Ngachan, S. V., & Bansal, K. C. (2015). Genetic diversity and population structure in aromatic and quality rice (*Oryza sativa* L.) landraces from North-Eastern India. PLoS ONE, 10(6), e0129607. https://doi.org/10.1371/journal.pone.0129607

Shivapriya, M., & Hittalmani, S. (2006). Detection of genotype-specific fingerprints and molecular diversity of selected Indian locals and landraces of rice (*Oryza sativa* L.) using DNA markers. Indian Journal of Genetics and Plant Breeding, 66(1), 1–5.

Siddique, M. A., Rashid, E. S. M. H., Khalequzzaman, M., Bashar, M. K., & Khan, L. R. (2014). Molecular characterization and genetic diversity in T. Aman landraces of rice (*Oryza sativa* L.) using microsatellite markers. Thai Journal of Agricultural Science, 47(4), 211–220.

Siddique, M. A., Khalequzzaman, M., Islam, M. M., Fatema, K., & Latif, M. A. (2016a). Molecular characterization and genetic diversity in geographical indication (GI) rice (*Oryza sativa* L.) cultivars of Bangladesh. Brazilian Journal of Botany. https://doi.org/10.1007/s40415-016-0271-1

Siddique, M. A., Khalequzzaman, M., Fatema, K., Islam, M. Z., Islam, M. M., & Chowdhury, M. A. Z. (2016b). Molecular characterization and genetic diversity of Aman rice (*Oryza sativa* L.) landraces in Bangladesh. Bangladesh Rice Journal, 20(2), 1–11.

Siddique, M. A., Khalequzzaman, M., Fatema, K., et al. (2017). DNA fingerprinting and genetic diversity in Aus rice (*Oryza sativa* L.) landraces of Bangladesh. Bangladesh Rice Journal, 21(1), 59–65.

Siddique, M. A., Khalequzzaman, M., Bhuiya, A., et al. (2023). Genetic diversity analysis in Boro rice (*Oryza sativa* L.) landraces of Bangladesh using SSR markers. Bangladesh Rice Journal, 27(2), 1–16.

Siddique, M. A., Islam, M. Z., Ahmed, M. S. U., & Khalequzzaman, M. (2025). Bangladesh Rice Research Institute (BRRI) genebank. In J. M. Al-Khayri, K. F. M. Salem, & S. M. Jain (Eds.), Plant gene banks. Springer. https://doi.org/10.1007/978-981-99-4236-7_32-1

Singh, N., Choudhury, D. R., Singh, A. K., Kumar, S., Srinivasan, K., & Tyagi, R. (2013). Comparison of SSR and SNP markers in estimation of genetic diversity and population structure of Indian rice varieties. PLoS ONE, 8(12), e84136. https://doi.org/10.1371/journal.pone.0084136

Singh, B. P., Singh, B., Mishra, S., Kumar, V., & Singh, N. K. (2016). Genetic diversity and population structure in Indian wild rice accessions. Australian Journal of Crop Science, 10(2), 144–151.

Song, Z. P., Li, B., Chen, J. K., & Lu, B. R. (2005). Genetic diversity and conservation of common wild rice (*Oryza rufipogon*) in China. Plant Species Biology, 20, 83–92.

Sun, C. Q., Wang, X. K., Li, Z. C., Yoshimura, A., & Iwata, N. (2001). Comparison of the genetic diversity of common wild rice (*Oryza rufipogon Griff.*) and cultivated rice (*O. sativa* L.) using RFLP markers. Theoretical and Applied Genetics, 102, 157–162.

Tamura, K., Peterson, D., Peterson, N., Stecher, G., Nei, M., & Kumar, S. (2011). MEGA5.1: Molecular evolutionary genetics analysis using maximum likelihood, evolutionary distance, and maximum parsimony methods. Molecular Biology and Evolution, 28, 2731–2739.

Thompson, J. A., Nelson, R. L., & Vodkin, L. O. (1998). Identification of diverse soybean germplasm using RAPD markers. Crop Science, 38(5), 1348–1355.

Thudi, M., & Fakrudin, B. (2011). Identification of unique alleles and assessment of genetic diversity of rabi sorghum accessions using simple sequence repeat markers. Journal of Plant Biochemistry and Biotechnology, 20(1), 74–83.

Vaughan, D. A. (1994). The wild relatives of rice: A genetic resources guidebook. International Rice Research Institute.

Vabna, F. A., Islam, M. Z., Prince, M. F. R. K., & Hoque, M. E. (2021). Molecular diversity analysis in Boro rice (*Oryza sativa* L.) landraces using SSR markers. Asian Journal of Biology, 12(1), 36–48.

Venkatesan, K., & Bhat, K. V. (2015). Microsatellite marker-based molecular characterization of small and medium-grained aromatic rice germplasm of Odisha, India. SABRAO Journal of Breeding and Genetics, 47(3), 248–259.

Wang, M. X., Zhang, H. L., Zhang, D. L., Qi, Y. W., Fan, Z. L., & Li, D. Y. (2008). Genetic structure of Oryza rufipogon Griff. in China. Heredity, 101, 527–535. https://doi.org/10.1038/hdy.2008.61

Wong, S., Yiu, P., Bong, S., Lee, H., Neoh, P., & Rajan, A. (2009). Analysis of Sarawak Bario rice diversity using microsatellite markers. American Journal of Agricultural and Biological Sciences, 4(4), 298–304.

Zhou, H. F., Xie, Z. W., & Ge, S. (2003). Microsatellite analysis of genetic diversity and population genetic structure of a wild rice (*Oryza rufipogon Griff.*) in China. Theoretical and Applied Genetics, 107, 332–339.

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Sustainable Rice Fertilization: Can Nano-Urea and Nano-Diammonium Phosphate Reduce Nitrogen and Phosphorus Inputs without Yield Penalties in Bangladesh?

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A B S T R A C T

Efficient fertilizer management is essential for sustaining rice productivity in Bangladesh while lowering production costs and minimizing environmental risks. This study examined whether liquid nano-urea (LNU) and liquid nano-diammonium phosphate (LND) could partially replace conventional prilled urea and diammonium phosphate (DAP) without yield penalties. Field experiments were conducted across six agro-ecological zones during the Boro 2022–23 and 2023–24 seasons, using randomized complete block designs with three replications. In the LNU experiment, various N rates and foliar sprays of nano-formulations were tested, whereas in the LND experiment, different P rates and foliar sprays of nano-formulations were evaluated. In 2022–23 at Gazipur, applying 66% of the recommended dose of prilled urea (RDPU) plus foliar LNU achieved yields (6.55 t ha^{-1}) statistically comparable to 100% RDPU (7.00 t ha^{-1}), saving 34% of urea. Multi-location trials in 2023–24 confirmed that yields from 66% RDPU with LNU often matched those from 100% RDPU, particularly in Gazipur, Cumilla, Habiganj, and Rajshahi. In Habiganj, two foliar sprays of LNU with 50% RDPU produced yields equivalent to those of 66% RDPU alone, indicating a potential to save 16% of urea. No significant yield differences were observed among LND treatments, and plots without phosphorus fertilization yielded similarly to those with 100% recommended P. This suggests that residual soil P supported crop growth during a single season, although long-term P omission could risk soil depletion. Overall, nano-urea enabled yield maintenance with up to one-third lower urea inputs, reducing input dependency and supporting national food security goals. Strategic use of 50% recommended P, with or without nano-DAP, may offer a sustainable pathway for phosphorus management in rice systems. However, long-term soil health impacts, economic feasibility, and farmer adoption dynamics require further investigation before large-scale recommendations can be made.

1. Introduction

Rice (*Oryza sativa* L.) remains one of humanity's most consequential crops, supplying a large share of daily calories across Asia and substantial portions of Africa and Latin America. Globally, rice occupies on the order of 160–165 million hectares and contributes roughly one-fifth of dietary energy supply, with Asia accounting for ~90% of both production and consumption (UN FAO, 2025). These figures

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underscore the centrality of rice to food security and livelihoods, particularly under rising demand and climatic stressors. The productivity gains achieved since the Green Revolution have depended heavily on mineral fertilizers, especially nitrogen (N) and phosphorus (P). Yet, agronomic and environmental inefficiencies remain large. Classic syntheses and subsequent global assessments indicate that nitrogen recovery efficiency in cereals often hovers near ~30–40%, implying that the majority of applied N is lost to the environment via volatilization, leaching, runoff, and denitrification (Islam et al., 2013a and 2013b; Raun et al., 2002; Islam et al., 2018). These losses erode farmer profitability and contribute to downstream pollution and greenhouse-gas (GHG) emissions (Islam et al., 2024; Islam et al., 2025). Likewise, global analyses report phosphorus use efficiency in cereals to be commonly below 20–25%, with large fractions of applied P becoming soil-fixed or transported to aquatic systems, thereby intensifying eutrophication risks and highlighting long-term concerns over finite phosphate rock resources (Yu et al., 2021).

The environmental externalities of current fertilizer paradigms are particularly salient in rice systems. The overutilization of synthetic fertilizers results in economic burdens and contributes to the escalation of pollution in soil, water, and the atmosphere. Nano fertilizers, engineered nutrient carriers or nano-scaled nutrient formulations designed to enhance delivery, uptake, and synchrony with crop demand have emerged as a promising (if still maturing) frontier. Reviews synthesize several hypothesized advantages: (i) high surface area and reactivity that improve solubility and mobility; (ii) potential for controlled or slow release; (iii) enhanced foliar absorption through stomatal or cuticular pathways; and (iv) opportunities for targeted delivery that reduce off-site losses. These features could, in principle, allow partial substitution of conventional urea and phosphate fertilizers while maintaining yields and improving NUE/PUE (Jakhar et al., 2022).

Within this space, nano-urea and nano-diammonium phosphate (nano-DAP) have attracted intense interest because they align directly with the dominant macronutrient constraints in rice. Field experiments and early multi-site trials from South Asia report that foliar nano-urea applied at critical growth stages can sustain grain yields while enabling reductions in conventional prilled urea (PU), and that nano-DAP may increase P uptake efficiency and yield components relative to equal or reduced doses of bulk DAP (Reddy et al., 2025; Sweety et al., 2024). However, the evidence base is heterogeneous across crops, seasons, and sites; and study designs vary in replication, formulation chemistry, and comparators, which complicates cross-study inference. In addition, nutrient uptake and use efficiency vary depending on plant genotypes, water management and the characteristics of fertilizers (Islam et al., 2015 and 2016; Rahman et al., 2014; Islam et al., 2023).

Recent controlled and field studies illustrate both the promise and the caveats. For nitrogen, a two-year field study comparing granulated vs. nano-urea in wheat and rice at the ICAR-IARI farm in New Delhi reported improvements in NUE metrics and comparable yields at reduced N input in nano-urea regimes, though effects were context-dependent and not uniformly superior in all environments, underscoring the need for season- and site-specific validation (Reddy et al., 2025). For phosphorus, several investigations have evaluated nano-formulated DAP and nano-hydroxyapatite (nHA) as more labile P sources. Some studies in rice and upland cereals document improved P uptake, photosynthetic performance, and yield with nano-P foliar sprays or seedling dips under reduced soil-applied P, while materials-science work on nHA suggests enhanced bioavailability with potential co-benefits for reducing metal(loid) mobility in flooded soils (Sahoo et al., 2024; Xiong et al., 2018). At the same time, reviews caution that nanoparticle–soil–microbe interactions are complex; benefits can be formulation-specific, and standardized efficacy and safety testing is still evolving.

Stepping back to the global challenge of nutrient management, the need for innovation in fertilizer technologies is widely recognized across both agronomic and policy domains. A recent Sustainable Agriculture review highlights novel fertilizers, including nano-formulations, as part of a broader portfolio to improve NUE and reduce losses, while emphasizing rigorous, independent evaluation, transparent labelling, and life-cycle assessment before widescale promotion (Maaz et al., 2025). In parallel, global cropland phosphorus budgets and systems analyses published in high-impact venues stress that raising PUE is essential both for resource security and for water-quality protection, given non-renewable phosphate rock reserves and the prevalence of harmful algal blooms in P-enriched watersheds (Zou et al., 2022). For countries such as Bangladesh—one of the world's largest rice producers—the intersection of food security goals, fertilizer import bills, and environmental limits makes the case for higher efficiency particularly compelling. But the question is fundamentally global: can nano-enabled N and P fertilization deliver equivalent or higher yields at lower input rates across diverse ecologies (from monsoonal lowlands to irrigated deltas and subtropical uplands), while also offering credible reductions in loss pathways (NH_3 volatilization, NO_3^- leaching, runoff) and supply-chain risks (e.g., P price shocks)?

In Bangladesh, where smallholder farmers often rely on excessive fertilizer use to achieve yield targets, the adoption of nano-urea and nano-DAP could significantly reduce fertilizer use and production costs while sustaining or improving rice productivity. However, limited field-based research has been conducted to evaluate their effectiveness under the diverse agroecological conditions of Bangladesh. Policymakers need credible cost–benefit analyses that incorporate subsidy structures and potential import substitutions for N and P fertilizers. The present study contributes to this agenda by examining whether nano-urea and nano-DAP can reduce nitrogen and phosphorus inputs without yield penalties under rice-growing conditions reflective of South Asia, particularly Bangladesh. By rigorously testing nano-urea and nano-DAP within this broader systems frame, we can more credibly judge their role in a diversified toolkit for resilient, climate-compatible rice intensification worldwide.

2. Materials and methods

2.1. Experimental site and season

Field experiments were conducted during the Boro 2022-23 season in Gazipur (AEZ 28) and the Boro 2023–24 season across six representative agro-ecological zones (AEZs) of Bangladesh: Gazipur (AEZ 28), Cumilla (AEZ 19), Habiganj (AEZ 20), Sonagazi (AEZ 18), Rajshahi (AEZ 11) and Satkhira (AEZ 13). These sites were selected to capture the diversity of soil properties, climatic conditions, and cropping patterns that characterize the country's major rice-growing regions. Bangladesh has a humid subtropical climate characterized by a monsoon season from May to October and a dry season from November to May. It receives approximately 2000 mm of rainfall annually, with an average temperature around 25 ˚C (Islam et al., 2025; Islam et al., 2024; Mainuddin et al., 2021). About 82–83% of this rainfall occurs during the wet season, from May to October (Mainuddin et al., 2021). Boro rice is grown during the dry season, which heavily relies on irrigation. In Boro 2022-23, LNU was tested at the BRRI farm in Gazipur using BRRI dhan89 as the test variety. In Boro 2023-24, trials were conducted at BRRI farms in Gazipur, Cumilla, Habiganj, Satkhira, Sonagazi, and Rajshahi, with BRRI dhan100, BRRI dhan74, BRRI dhan104, BRRI dhan89, BRRI dhan107, and BRRI dhan102 used as test varieties, respectively. Soil samples (0–15 cm depth) were collected prior to ploughing at each site to determine baseline soil characteristics, including pH (Glass electrode method), organic carbon (Walkley and Black wet digestion method), total nitrogen (Micro-Kjeldahl method), and available phosphorus (Modified Olsen method), following the procedures described by Saha et al. (2016). The soil pH ranged from slightly acidic in Habiganj (pH 5.6) to slightly alkaline in Satkhira (pH 7.9) and Rajshahi (pH 7.5), with variable organic carbon (0.90–1.32%), total nitrogen contents (0.09–0.13%), and available phosphorus (13-35 mg kg^{-1}).

2.2 Experimental design and layout

A randomized complete block design was employed with three replications at each location. The individual plot size was 20 m^2 (4.0 m × 5.0 m), with 30 cm bunds separating adjacent plots to prevent the movement of water and fertilizer. Treatment details are presented in Tables 1 and 2. The experiment was designed to assess the potential of nano-urea and nano-DAP (experimental formulations) to partially replace prilled urea and conventional diammonium phosphate (DAP) without affecting yield.

Table 1
Treatment combinations of liquid nano-urea (LNU) trial at different locations, Boro 2022-23 and 2023-24.

Boro 2022-23	Boro 2023-24
T_1: 66% recommended dose of prilled urea (RDPU) at basal and active tillering	T_1: 50% recommended dose of prilled urea (RDPU) at basal
T_2: 66% RDPU (33% at basal and 33% at active tillering) + two foliar sprays of LNU (at max. tillering and one week before flowering)	T_2: 50% RDPU at basal + two foliar sprays of LNU (at max. tillering and one week before flowering)
T_3: 100% RDPU (33% at basal + 34% at active tillering + 33% at max. tillering)	T_3: 33% RDPU at basal + 33% RDPU at active tillering
T_4: 100% RDPU (33% at basal + 34% at active tillering + 33% at max. tillering) + two foliar sprays of LNU (max. tillering and one week before flowering)	T_4: 33% RDPU at basal + 33% RDPU at active tillering + two foliar sprays of LNU (at max. tillering and one week before flowering)
	T_5: 100% RDPU (33% at basal + 34% at active tillering + 33% at max. tillering)

Table 2
Treatment combinations of liquid nano-DAP (LND) trial at different locations, Boro 2023-24.

Boro 2023-24
T_1 : 50% of the recommended doses of P (RDP) at basal
T_2 : 50% RDP at basal + one foliar spray of LND at 20-25 DAT
T_3 : Root dipping of seedlings with LND + 50% RDP at basal + one foliar spray of LND at 20-25 DAT
T_4 : 50% RDP at basal + two foliar sprays of LND at 20-25 DAT and 45-55 DAT
T_5 : Root dipping of seedlings with LND + 50% RDP at basal + two foliar sprays of LND at 20-25 DAT and 45-55 DAT
T_6 : 100% RDP at basal

The recommended dose of fertilizers was based on the Fertilizer Recommendation Guide (Hossain et al, 2024), varying slightly across sites according to soil fertility status. The recommended dose of N was 174 kg ha^{-1} for the Boro season in all locations. The dose of LNU/LND was 1235 ml ha^{-1}, and the solution concentration was 4 ml L^{-1} of water.

2.3. Crop management

Two to three seedlings were transplanted per hill with a spacing of 20 cm by 20 cm. Urea fertilizer was administered in three equal doses at the basal stage, during maximum tillering, and at panicle initiation. The full dose of P, K, S, and Zn was applied during final land preparation using TSP, MoP, gypsum, and zinc sulphate. Liquid nano-urea was sprayed as a foliar at maximum tillering and one week before flowering. Liquid nano-DAP was applied by seedling root dipping before transplanting and as a foliar spray at 20–25 and 45–50 days after transplanting (DAT). Other agronomic practices, including weed and pest management, were implemented following BRRI recommendations.

Rice was harvested at physiological maturity from a central 5 m^2 area (125 hills) in each plot to determine grain yield. The grains were winnowed, sun-dried, and adjusted to a standard 14% moisture content, with yields expressed in t ha^{-1}.

2.4. Statistical analysis

Grain yield data were analyzed using STAR 2.0.1 software (IRRI, Philippines). A randomized complete block design (RCBD) was used for the analysis of variance (ANOVA), and treatment means were compared using Tukey's Honest Significant Difference (HSD) test at the 5% significance level.

3. Results

In the Boro 2022-23 season, urea fertilizer application had a significant impact on rice grain yield (Table 3). The lowest yield of 5.74 t ha^{-1} was recorded with the application of 105.6 kg N ha^{-1} (66% RDPU, T_1), which was significantly lower than other treatments. However, spraying LNU alongside 66% RDPU (T_2) increased the grain yield to 6.55 t ha^{-1}, marking a 14% improvement over T_1. The highest yield of 7.00 t ha^{-1} was obtained with the application of 160 kg N ha^{-1} (100% RDPU, T_3), which was statistically similar to T_2 (66% RDPU + LNU). The LNU treated plot with reduced dose (66%) of prilled urea (T_2) yielded higher net benefits of 198663 Tk ha^{-1}, compared to the similar doses of prilled urea (PU) treated plot (T_1) of 180522 Tk ha^{-1}. However, the highest net benefit (214786 Tk ha^{-1}) was found in T_3 (100% of RDPU) treatment (Table 6).

Table 3
Effect of liquid nano-urea (LNU) on the grain yield of BRRI dhan89 at BRRI farm, Gazipur, in Boro 2022-23.

Treatment	Grain yield (t ha^{-1})
T_1 : 66% recommended dose of prilled urea (RDPU) at basal and early tillering	5.74 c
T_2 : 66% RDPU (33% at basal and 33% at early tillering) + two foliar sprays of LNU (at max. tillering and one week before flowering)	6.55 ab
T_3 : 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering)	7.00 a
T_4 : 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering) + two foliar sprays of LNU (max. tillering and one week before flowering)	6.48 b
Level of significance	**
CV	3.8

In the Boro 2023-24 season, the effects of LNU on rice yield are presented in Table 4. In Gazipur, Cumilla, Habiganj and Satkhira sites, 100% of RDPU (T_5) gave the highest grain yield, which was statistically similar to T_3 (66% of RDPU) and T_4 (two foliar sprays of LNU along with 66% of RDPU). So, it indicates that 66% of RDPU is sufficient for obtaining optimum rice yield. However, in the Habiganj site, the T_3 treatment (66% of RDPU) gave a statistically identical yield to the T_2 (two foliar sprays of LNU along with 50% of RDPU) treatment. This indicates that LNU may save 16% of prilled urea without sacrificing rice yield in the Boro season. A significant yield difference between the T_1 (50% of RDPU) and T_2 (two foliar sprays of LNU along with 50% of RDPU) treatments in Cumilla and Habiganj sites also indicates that the foliar spray of LNU might have positive effects on rice yield in the Boro season. In contrast, no yield difference was found between the T_1 and T_2 treatments in the Gazipur, Satkhira and Rajshahi sites. In Rajshahi, the highest grain yield was obtained from T_5 (100% RDPU), which was statistically similar to T_4 (two foliar sprays of LNU with 66% RDPU), indicating that LNU could reduce prilled urea use by 34% without yield loss. Notably, no significant yield differences among treatments were observed at the Sonagazi site. Moreover, the highest net benefit (218446-258726 Tk ha^{-1}) was found from the recommended dose of prilled urea (T_5) in all locations except in Satkhira (Table 6).

Table 4
Effect of liquid nano-urea (LNU) on the grain yield of rice in Boro 2023-24.

Treatment	Grain yield (t ha^{-1})					
	Gazipur (BRRI dhan 100)	**Cumilla (BRRI dhan74)**	**Habiganj (BRRI dhan104)**	**Satkhira (BRRI dhan89)**	**Rajshahi (BRRI dhan102)**	**Sonagazi (BRRI dhan107)**
T_1	5.71 b	5.71 c	6.04 c	4.11 b	5.19 c	7.55
T_2	6.17 b	6.81 b	6.61 b	4.41 b	5.26 c	7.71
T_3	6.77 a	7.68 a	6.89 ab	6.46 a	6.20 b	7.49
T_4	7.05 a	7.79 a	6.70 ab	6.02 a	6.96 ab	7.65
T_5	7.12 a	8.39 a	7.19 a	6.18 a	7.47 a	7.90
Level of significance	**	***	**	***	***	NS
CV	3.84	5.60	4.13	6.31	6.85	3.74

Means with the same letter are not significantly different. NS = non-significant at 5% level of significance. T_1: 50% recommended dose of urea (RDU) at basal; T_2: 50% RDU at basal + two foliar spray of LNU (at max. tillering and one week before flowering); T_3: 33% RDU at basal + 33% RDU at active tillering; T_4: 33% RDU at basal + 33% RDU at active tillering + two foliar spray of LNU (at max. tillering and one week before flowering); T_5: 100% RDU (33% at basal + 34% at active tillering + 33% at max. tillering).

The effects of LND on rice yield are presented in Table 5. There were no significant variations in rice yield among the treatments at any location. No yield difference between the treatments of 50% (T_1) and 100% (T_6) recommended dose of P fertilizer in the Boro season was observed.

Table 5
Effect of liquid nano-DAP (LND) on the grain yield of rice in Boro 2023-24.

Treatment	Grain yield (t ha^{-1})		
	Habiganj (BRRI dhan104)	**Rangpur (BRRI dhan102)**	**Rajshahi (BRRI dhan107)**
T_1	7.20	7.37	6.27
T_2	7.09	7.63	6.82
T_3	7.19	7.33	6.63
T_4	7.26	7.34	6.68
T_5	7.31	7.26	7.12
T_6	7.42	7.67	7.14
Level of significance	NS	NS	NS
CV	3.53	2.13	8.73

T_1: 50% of recommended doses of P (RDP) at basal; T_2: 50% RDP at basal + one foliar spray of LND at 20-25 DAT; T_3: Root dipping of seedlings with LND + 50% RDP at basal + one foliar spray of LND at 20-25 DAT; T_4: 50% RDP at basal + two foliar spray of LND at 20-25 DAT and 45-55 DAT; T_5: Root dipping of seedlings with LND + 50% RDP at basal + two foliar spray of LND at 20-25 DAT and 45-55 DAT; T_6: 100% RDP at basal.

Table 6
Economic analysis of liquid nano-urea (LNU) for Boro rice cultivation in 2022-23 and 2023-24.

Treatments	Net Benefit (Tk ha^{-1})						
	2022-23	**2023-24**					
	Gazipur	Gazipur	Cumilla	Habiganj	Satkhira	Rajshahi	Sonagazi
T_1	180522	181142	182742	193342	128292	166042	246092
T_2	198663	189363	209633	204913	130953	161423	244503
T_3	214786	212002	240912	217692	198182	195202	242442
T_4	192927	213863	237683	205313	178203	210893	240463
T_5	-	218446	258726	223486	186086	229596	251106

Total variable cost includes the price of fertilizer, labor cost for fertilizer application and additional products and by-products, as other costs were similar in all treatments. Urea = 27 Tk kg^{-1}, TSP = 27 Tk kg^{-1}, MoP = 20 Tk kg^{-1}, Gypsum = 20 Tk kg^{-1}, Zinc = 350 Tk kg^{-1}, liquid nano-urea = 1700 Tk/500 ml (3.4 Tk/ml), price of paddy = 30 Tk kg^{-1}, price of straw = 5 Tk kg^{-1}, laborer wage = 500 Tk day^{-1}, five additional laborers/ha were required for fertilizer application and five for spraying of LNU, four additional laborers were required for one ton additional products and by-products. In Boro 2022-23, T_1 = 66% recommended dose of prilled urea (RDPU) at basal and early tillering; T_2 = 66% RDPU (33% at basal and 33% at early tillering) + two foliar sprays of LNU (at max. tillering and one week before flowering); T_3 = 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering); T_4 = 100% RDPU (33% at basal + 34% at early tillering + 33% at max. tillering) + two foliar spray of LNU (max. tillering and one week before flowering). In Boro 2023-24, T_1 = 50% recommended dose of urea (RDU) at basal; T_2 = 50% RDU at basal + two foliar spray of LNU (at max. tillering and one week before flowering); T_3 = 33% RDU at basal + 33% RDU at active tillering; T_4 = 33% RDU at basal + 33% RDU at active tillering + two foliar spray of LNU (at max. tillering and one week before flowering); T_5 = 100% RDU (33% at basal + 34% at active tillering + 33% at max. tillering).

4. Discussion

The present study demonstrates that nano-urea, when strategically integrated with conventional fertilizer management, can sustain rice yields in some AEZ of Bangladesh, while reducing nitrogen (N) fertilizer inputs. This finding has profound implications for sustainable intensification in Bangladesh and other rice-based systems worldwide, where rising input costs, environmental degradation, and climate variability are pressing concerns. However, nano-DAP might not respond positively to increasing rice production.

One of the most compelling outcomes was the ability of nano-urea to maintain yields at up to 33% lower prilled urea input. This aligns with previous research indicating that foliar-applied nano-fertilizers enhance nutrient use efficiency by bypassing soil-related losses such as volatilization, leaching, and denitrification (Reddy et al., 2025). Plant growth and yield responses depend on various climatic conditions (Islam et al., 2022). Nitrogen losses from conventional urea in flooded rice systems are particularly high, often exceeding 50–70% of applied N (Coskun et al., 2017). By directly supplying N to the leaves in nano-form, uptake efficiency is substantially increased, thereby explaining the observed equivalence in yield between reduced-dose treatments and the full recommended dose (Jakhar et al., 2022; Reddy et al., 2025).

The absence of significant yield differences between the 100% RDPU treatment and reduced RDPU (66%) with nano-urea (Table 4) indicates that Bangladesh can achieve food security goals with lower input dependency. Similar results were reported in India, where the Indian Council of Agricultural Research (ICAR) validated that nano-urea could replace 25–30% of conventional urea without yield penalties across several crops, including rice and wheat (Upadhyay et al., 2023). Likewise, trials in Africa and Southeast Asia have confirmed comparable yield sustainability under reduced inputs when nano-fertilizers are integrated (Khundi et al., 2025). This finding is particularly relevant for Bangladesh, where fertilizer imports constitute a significant portion of the agricultural subsidy budget, and price volatility has strained both government and farmers (Alam, 2018). By enabling substantial fertilizer savings, nano-urea adoption can reduce the financial burden while maintaining production, thereby aligning with Sustainable Development Goal (SDG) 2 of ending hunger and promoting sustainable agriculture.

For phosphorus, the observation that Boro rice yields did not differ significantly between phosphorus-omitted plots and those receiving the full recommended dose of DAP (Table 5) suggests that phosphorus omission in a single season might not necessarily reduce rice yield. In the context of Bangladesh, this phenomenon is likely attributable to residual soil phosphorus accumulation from previous fertilization, which may often sustain rice production even in the absence of fresh P inputs. In Bangladesh, it is indicated that the critical soil P threshold—as measured by Olsen P—is approximately 10 mg kg^{-1}; soils above this level typically show limited yield response to additional P fertilization (Hossain et al., 2024). This implies that in soils with phosphorus levels exceeding this critical value, rice plants may extract sufficient P from the soil legacy pool, negating the need for seasonal fertilizer in the short term. Further, phosphorus availability in wetland (paddy) soils—such as those under Boro cultivation—is often enhanced due to reductive dissolution of soil Fe and Al compounds, which frees sorbed phosphorus and increases its plant availability (Choudhury et al., 2007). This environmental mechanism might further bolster soil-derived P supply, thereby diminishing the immediate response to additional DAP application.

However, it is essential to interpret these findings within a broader agronomic and environmental context. Continued omission of P fertilizer over multiple seasons—especially in high-extraction cropping systems like intensively managed Boro rice—could eventually deplete residual P pools, leading to deficiencies and yield decline. Therefore, even if an individual season shows no significant yield gap between treatments, P fertilization remains crucial for long-term soil fertility maintenance and sustained productivity. Phosphorus legacies and soil redox dynamics may buffer rice yield against short-term P omission in highly fertilized Bangladeshi soils. Yet, for sustainable management, phosphorus inputs must still be adjusted over time in response to soil P trends, crop demand, and environmental considerations. Therefore, either a reduced application of P fertilizer at 50% of the recommended dose or the combined use of foliar-applied nano-DAP with 50% of the recommended dose may serve as suitable strategies for sustainable rice production.

Excessive N and P application has long been associated with negative environmental externalities, including greenhouse gas (GHG) emissions, eutrophication, and soil degradation (Gaihre et al., 2018; Xia et al., 2020). In flooded rice systems, urea-derived N is a major source of nitrous oxide (N_2O) and methane (CH_4), potent greenhouse gases (Bhuiyan et al., 2021). By improving NUE, nano-urea reduces the potential for excess N losses, thereby lowering the environmental footprint of rice production. Phosphorus over-application has also led to the accumulation of residual P in soils, increasing the risk of runoff into water bodies and contributing to harmful algal blooms (Ngatia and Taylor, 2018). By reducing the reliance on bulk P fertilizers, nano-DAP provides a pathway to more precise nutrient management and mitigates such risks. Therefore, the current results not only support economic sustainability but also environmental stewardship.

The efficiency of nano-urea and nano-DAP is linked to their smaller particle size, higher surface area, and greater solubility, which enhance absorption and translocation within the plant (Nongbet et al., 2022). In the case of nano-urea, direct foliar absorption allows for immediate assimilation, especially during critical growth stages such as tillering and panicle initiation, when N demand peaks (Namasharma et al., 2023; Nongbet et al., 2022). Similarly, nano-DAP applied during early vegetative and reproductive stages likely enhances P availability for root development, tiller production, and grain filling. From the present study, site-specific variability in yield response was observed. Nano-urea performed particularly well in Gazipur and Rajshahi soils with lower organic matter and N. This aligns with findings by Belyaeva et al. (2024), who showed that NUE gains are more pronounced under conditions of high N losses.

While the study highlights the potential of nano-urea and nano-DAP in rice production, several limitations remain and warrant further investigation. Firstly, the long-term effects of nano-fertilizers on soil health are not fully understood. Emerging research suggests that these materials may alter microbial communities and soil enzyme activities—factors vital for nutrient cycling and soil function (Zhang et al., 2024). Secondly, the economic viability of nano-formulations at scale requires careful evaluation. Although their precise delivery mechanisms seem promising, the costs associated with large-scale production, distribution, and regulatory approval remain uncertain, and real-world supply chains have yet to be tested. Equally important is understanding farmer perceptions and adoption behavior. Recent studies indicate that smallholder farmers are hesitant to adopt innovations perceived as risky or costly unless clear benefits are demonstrated, with access to extension services and credit playing critical roles in adoption decisions (Kule et al., 2025). Finally, the environmental fate and potential toxicity of nano-fertilizers must be rigorously monitored; unintended soil or water contamination could negate their agronomic advantages (Kekeli et al., 2025). Addressing these knowledge gaps is crucial for ensuring that nano-fertilizers become a safe, economical, and widely adopted component of sustainable agriculture.

Moreover, combining nano-fertilizers with complementary practices such as conservation agriculture, alternate wetting and drying (AWD), and precision agriculture technologies can amplify benefits. For example, AWD reduces methane emissions while improving water-use efficiency; integrating nano-urea under AWD could create synergistic effects for both yield and environmental outcomes. Similarly, precision tools such as drone-based foliar sprays could further enhance the effectiveness of nano-fertilizer delivery.

5. Conclusion

This study provides compelling evidence that nano-urea can play a transformative role in sustainable rice production in different locations of Bangladesh and other rice-growing regions worldwide. By partially substituting conventional prilled urea with foliar-applied nano-urea, it is possible to reduce nitrogen inputs without compromising grain yield. The results highlight that nano-urea can effectively replace up to one-third of prilled urea in some locations, while the efficacy of nano-DAP is still mysterious. These findings align with the broader goals of resource-efficient agriculture, offering a pathway to improved farm profitability and reduced dependence on fertilizer imports. Despite these promising outcomes, several caveats remain. LNU may not be economically viable, as it demonstrated a lower net benefit compared to the recommended doses of prilled urea. Long-term effects of nano-fertilizer application on soil microbial health, nutrient cycling, and environmental safety require further research. Additionally, socio-economic factors such as farmer awareness, adoption behaviour, and affordability at scale must be carefully addressed through participatory trials, extension programs, and policy support.

References

Alam, M. A. U. (2018). The effect of the 'subsidy on fertilizer'on food prices in Bangladesh and policy options. Journal of Economics and Sustainable Development, 9, 200-208.

Belyaeva, O., Ward, G., Wijesinghe, T., Chen, D., & Suter, H. (2024). Influence of soil organic matter, fertiliser formulation and season on fertiliser nitrogen use efficiency in temperate pastures. Nutrient Cycling in Agroecosystems, 129(1), 133-150.

Bhuiyan, M. S. I., Rahman, A., Kim, G. W., Das, S., & Kim, P. J. (2021). Eco-friendly yield-scaled global warming potential assists to determine the right rate of nitrogen in rice system: A systematic literature review. Environmental Pollution, 271, 116386.

Choudhury, A. T. M. A., Kennedy, I. R., Ahmed, M. F., & Kecskés, M. L. (2007). Phosphorus fertilization for rice and control of environmental pollution problems. Pakistan Journal of Biological Sciences, 10(13), 2098-2105.

Coskun, D., Britto, D. T., Shi, W., & Kronzucker, H. J. (2017). Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. Nature plants, 3(6), 1-10.

Gaihre, Y. K., Singh, U., Islam, S. M. M., Huda, A., Islam, M. R., Sanabria, J., Satter, M.A., Islam, M.R., Biswas, J.C., Jahiruddin, M. & Jahan, M. S. (2018). Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields. Nutrient Cycling in Agroecosystems, 110(2), 277-291.

Hossain, M. B., Jahiruddin, M., Chowdhury, M. A., Naser, H. M., Anwar, M. M., Islam, A., Haque, M. A., Alim, M. A., Hossain, G. M. A., Islam, M. A., Hossain, A., Satter, M. A., & Alam, F. (2024). Fertilizer Recommendation Guide-2024. Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka-1215, Bangladesh. https://apps.barc.gov.bd/fertilizer_recommendation/FRG%20English%2030.10.2024.pdf

Islam, M. N., Bell, R. W., Barrett-Lennard, E. G., & Maniruzzaman, M. (2025). Shallow drains and straw mulch alleviate multiple constraints to increase sunflower yield on a clay-textured saline soil I. Effects of decreased soil salinity, waterlogging and end-of-season drought. European journal of agronomy, 162, 127416.

Islam, M. N., Bell, R. W., Barrett-Lennard, E. G., & Maniruzzaman, M. (2022). Growth and yield responses of sunflower to drainage in waterlogged saline soil are caused by changes in plant-water relations and ion concentrations in leaves. Plant and Soil, 479(1), 679-697.

Islam, M. N., Alam, F., Saha, P. K., Shah, A. L., Islam, A., & Biswas, J. C. (2015). Effect of magic growth on rice yield. Bangladesh Rice Journal, 19(2), 91-97.

Islam, M. N., Islam, A., & Biswas, J. C. (2016). Genotypic variations in modern rice and nitrogen use efficiency. International Journal of Agricultural Papers, 1(2), 27-35.

Islam, M. N., Rahman, M. M., Mian, M. J. A., Barua, R., & Kamal, A. M. (2013a). Leaching loss of NPKS in silty soil under alternate wetting and drying condition. Eco-friendly Agriculture Journal, 6(04), 67-71.

Islam, M. N., Rahman, M. M., Mian, M. J. A., Barua, R., & Kamal, A. M. (2013b). Leaching loss of NPKS in the Old Brahmaputra Floodplain soil under continuous standing water condition. Eco-friendly Agriculture Journal, 6(04): 63-66

Islam, S. M. M., Gaihre, Y. K., Islam, M. N., Jahan, A., Sarkar, M. A. R., Singh, U., Islam, A., Al Mahmud, A., Akter, M., & Islam, M. R. (2024). Effects of integrated nutrient management and urea deep placement on rice yield, nitrogen use efficiency, farm profits and greenhouse gas emissions in saline soils of Bangladesh. Science of the Total Environment, 909, 168660.

Islam, S. M. M., Gaihre, Y. K., Islam, M. N., Suvo, T. P., Sander, B. O., Habib, M. A., Islam, A., Nayak, S., Singh, U., Hasegawa, T., & Islam, M. R. (2025). Reducing greenhouse gas emissions and improving rice yield: The influence of cultivars, soil salinity, and nitrogen management. Science of The Total Environment, 997, 180192.

Islam, S. M. M., Gaihre, Y. K., Biswas, J. C., Jahan, M. S., Singh, U., Adhikary, S. K., Satter, M. A., & Saleque, M. A. (2018). Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: Fate of nitrogen and grain yield. Agricultural Water Management, 196, 144-153.

Islam, S. M. M., Gaihre, Y. K., Islam, M. R., Islam, A., Singh, U., & Sander, B. O. (2023). Effects of integrated plant nutrition systems with fertilizer deep placement on rice yields and nitrogen use efficiency under different irrigation regimes. Heliyon, 9(12).

Jakhar, A. M., Aziz, I., Kaleri, A. R., Hasnain, M., Haider, G., Ma, J., & Abideen, Z. (2022). Nano-fertilizers: A sustainable technology for improving crop nutrition and food security.

NanoImpact, 27, 100411.
Kekeli, M. A., Wang, Q., & Rui, Y. (2025). The role of nano-fertilizers in sustainable agriculture: Boosting crop yields and enhancing quality. Plants, 14(4), 554.
Khundi, Q., Jiang, Y., Sun, Y., & Rui, Y. (2025). Nanofertilizers for Sustainable African Agriculture: A Global Review of Agronomic Efficiency and Environmental Sustainability. Nanomaterials, 15(5), 390.
Kule, E. K., Obia, A., Agole, D., Okello, D. M., & Odongo, W. (2025). Farmer perceptions and their implications for adoption of sustainable agricultural intensification practices. Discover Sustainability, 6(1), 210.
Maaz, T. M., Dobermann, A., Lyons, S. E., & Thomson, A. M. (2025). Review of research and innovation on novel fertilizers for crop nutrition. npj Sustainable Agriculture, 3(1), 25.
Mainuddin, M., Karim, F., Gaydon, D. S., & Kirby, J. M. (2021). Impact of climate change and management strategies on water and salt balance of the polders and islands in the Ganges delta. Scientific reports, 11(1), 7041.
Namasharma, S., Pahari, A., Banik, A., Pal, S., Sana, M., Pal, S., & Banerjee, H. (2023). Impact of foliar applied nano-urea on growth, productivity and profitability of hybrid rice (*Oryza sativa* L.). Oryza, 60(3), 464-472.
Ngatia, L., & Taylor, R. (2018). Phosphorus eutrophication and mitigation strategies. In H. Ohtake, & S. Tsuneda (Eds.), Phosphorus-recovery and recycling (pp. 45-61). InTech, Rijeka, Croatia.
Nongbet, A., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Ray, M. K., Khan, M., Baek, K.H., & Chakrabartty, I. (2022). Nanofertilizers: a smart and sustainable attribute to modern agriculture. Plants, 11(19), 2587.
Rahman, M. S., Islam, M. N., Hassan, M. Z., Islam, S. A., & Zaman, S. K. (2014). Impact of water management on the arsenic content of rice grain and cultivated soil in an arsenic contaminated area of Bangladesh. Journal of Environmental Science and Natural Resources, 7(2), 43-46.
Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L., Mullen, R. W., Freeman, K. W., Thomason, W.E., & Lukina, E. V. (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal, 94(4), 815-820.
Reddy, K. S., Shivay, Y. S., Kumar, D., Pooniya, V., Prasanna, R., Mandi, S., Nayak, S., Baral, K., Alekhya, G., & Borate, R. B. (2025). Relative performance of granulated and nano urea on productivity and nitrogen use efficiency of wheat–rice sequence. Plant Nano Biology, 11, 100131.
Saha, P. K., Islam, S., Islam, M. N., Biswas, J. C., & Haque, M. M. (2016). Soil plant nutrient status under intensive rice-farming systems in unfavorable eco-systems of Bangladesh. International Journal of Chemical and Pharmaceutical, 2(2), 1-13.
Sahoo, B. R., Dash, A. K., Mohapatra, K. K., Mohanty, S., Sahu, S. G., Sahoo, B. R., Prusty, M., & Priyadarshini, E. (2024). Strategic management of nano-fertilizers for sustainable rice yield, grain quality, and soil health. Frontiers in Environmental Science, 12, 1420505.
Sweety, R., Boominathan, P., Senthil, A., Jegadeeswari, D., & Kumar, G. P. (2024). Nano-diammonium phosphate enhances grain yield by modulating gas exchange traits and nutrient use efficiency in rice. Plant Science Today, 11(sp4).
UN FAO. (2025). Our World in Data. “Production: Crops and livestock products” [original data]. Food and Agriculture Organization of the United Nations. Retrieved August 19, 2025 from https://archive.ourworldindata.org/20250731-180103/grapher/rice-production.html
Upadhyay, P. K., Dey, A., Singh, V. K., Dwivedi, B. S., Singh, T., GA, R., Babu, S., Rathore, S.S., Singh, R.K., Shekhawat, K., & Shukla, G. (2023). Conjoint application of nano-urea with conventional fertilizers: An energy efficient and environmentally robust approach for sustainable crop production. Plos one, 18(7), e0284009.
Xia, Y., Zhang, M., Tsang, D. C., Geng, N., Lu, D., Zhu, L., Igalavithana, A. D., Dissanayake, P. D., Rinklebe, J., Yang, X., & Ok, Y. S. (2020). Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: current practices and future prospects. Applied Biological Chemistry, 63(1), 8.
Xiong, L., Wang, P., Hunter, M. N., & Kopittke, P. M. (2018). Bioavailability and movement of hydroxyapatite nanoparticles (HA-NPs) applied as a phosphorus fertiliser in soils. Environmental Science: Nano, 5(12), 2888-2898.
Yu, X., Keitel, C., & Dijkstra, F. A. (2021). Global analysis of phosphorus fertilizer use efficiency in cereal crops. Global Food Security, 29, 100545.
Zhang, H., Zheng, T., Wang, Y., Li, T., & Chi, Q. (2024). Multifaceted impacts of nanoparticles on plant nutrient absorption and soil microbial communities. Frontiers in plant science, 15, 1497006.
Zou, T., Zhang, X., & Davidson, E. A. (2022). Global trends of cropland phosphorus use and sustainability challenges. Nature, 611(7934), 81-87.

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Trade-Offs in Rice Pest Management: Enhanced Biological Control and Yield Equivalence Compared with Prophylactic Insecticide Use

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ABSTRACT

The study was conducted in four consecutive T. Aman seasons from 2021 to 2024 at the experimental farm of the Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh, to evaluate the impacts of insecticide application on the abundance of harmful and beneficial arthropods in rice ecosystems, comparing conventional farmer practices (prophylactic insecticide application) and researcher-guided practices (need based/rational). Prior to insecticide application, no significant differences were observed in the populations of both harmful insects and beneficial arthropods, confirming a balanced initial baseline. After the 1st and 2nd insecticide applications, several pest species-including yellow stem borer (YSB), green leafhopper (GLH), rice leafroller (RLR), white leafhopper (WLH), brown planthopper (BPH), short-horned grasshopper (SHG), and white-backed planthopper (WBPH) showed significantly higher abundance in researcher-guided plots, suggesting that insecticide use initially suppressed insect pests but later (after 3rd application) rebound. Conversely, all studied natural enemies were consistently and significantly more abundant in researchers-guided plots throughout all sampling periods indicated that, insecticide applications reduce pest populations rapidly and temporarily, but also drastically diminish the abundance of natural enemy, disrupting biological control and fostering potential pest resurgence risk. The higher parasitism rates of BPH (20.20%), RLR (26.78%), and YSB (27.56%) in researcher-practice fields further highlight the contribution of parasitoids and predators to natural pest suppression. Despite reduced chemical insecticide applications, rice yield showed no significant difference between researcher practice (6.21 t ha^{-1}) and prophylactic insecticide-applied (6.23 t ha^{-1}) plots. The findings underscore that judicious or minimal insecticide use guided by economic threshold levels can conserve natural enemies, sustain pest regulation, and maintain yield stability.

1. Introduction

Rice (*Oryza sativa* L.) remains the world's most vital cereal crop, particularly in Asia. In Bangladesh, rice is a dietary staple and a key determinant of national food security. More than half of the world population primarily depends on rice, specifically in Asia, Latin America, the middle-East and the West Indies. The people of Bangladesh primarily depend on rice and rice consumed here as a staple food and so rice plays a crucial role for ensuring food security. There are three rice cultivation seasons namely; Aus, Aman and Boro, and extensively cultivated throughout the year. However, insect pests pose persistent threats to rice productivity, attacking crops from seedling to maturity. Farmers in Bangladesh typically apply

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insecticides 3–5 times per season (Roy et al., 2025a), often before pest densities reach economic thresholds. While these inputs provide short-term relief, they suppress beneficial arthropods, promote pest resistance, and degrade environmental quality. The production of rice decreases directly and indirectly due to presence of insect-pests at different growth stage of rice from seedling to maturity (Roy et al., 2024). Some arthropods complete their life cycle in rice plant; some are used as host plants. About 232 harmful insect species and 375 natural enemy species have been recorded, and only 20-33 species are identified as the most economically damaging insect pests (Ali et al., 2019; Islam and Catling, 2012; Roy et al., 2024; Roy et al., 2025b). The major pest species of significant concern in Bangladesh encompasses the rice leaf folders (*Cnaphalocrocis medinalis* Guenée), stem borer (*Scirpophaga incertula* Walker), green leafhopper (*Nephotettix virescens* Distant), brown planthopper (*Nilaparvata lugens* Stal°), rice hispa (*Dicladispa armigera* Olivier), white-backed planthopper (*Sogatella furcifera* Horv´ath), small brown planthopper (*Laodelphax striatellus* Fallen), and gall midge (*Orseolia oryzae*, Wood-mason) as substantiated by a recent investigation (Ali et al., 2019; Islam and Catling, 2012; Roy et al., 2025a). Among the insect pests, some are directly damage plants by feeding on leaves, cell sap sucking from stem, internal feeder, grain sucking etc.

Farmers in Bangladesh depends heavily on synthetic insecticides to manage rice insect pests because of their easy availability, active marketing, relatively low cost, ease of use, and quick efficacy in either eliminating insect pests or changing their detrimental habits (Horgan et al., 2021; Roy, et al., 2025a). Farmers of Bangladesh normally use 3-5 times pesticides for rice cultivations (Roy et al., 2025a). Application of insecticides not only kill insect pests but also make them resistance against insecticides. In addition, farmers of Bangladesh start insecticide application from early stage of rice when pest populations might under the economic threshold levels (Bari et al., 2015). Moreover, insecticides negatively influence the habitat of natural enemies, human health and the environment. The natural enemies (comprising parasitoids and predators) perform diverse ecological roles. Which engage from herbivory on rice plants to pollination, parasitization, predation, nutrient cycling and decomposition (Bari et al., 2025). The intricate relationships among rice plants, insect-pests, and numerous natural enemy species are designed to create equilibrium and prevent epidemics of abnormal pests. So, to protect natural enemies some strategies need to take. Natural enemies, predators and parasitoids can play critical ecological roles by maintaining pest populations below outbreak levels. Hence, strategies such as ecological engineering and rational insecticide use are essential to protect natural enemies and foster sustainable pest regulation (Bari et al., 2025). Nevertheless, information remains limited regarding the long-term effects of prophylactic insecticide applications on pest-natural enemy interactions in Bangladeshi rice ecosystems. Therefore, the present study was undertaken to compare continuous insecticide application (farmer practice) with rational/ need-based application (researcher practice), focusing on pest and natural enemy dynamics and their influence on grain yield, with the objective of identifying a more sustainable and ecologically sound pest management strategy for rice production in Bangladesh.

2. Materials and methods

2.1. Study Area

The present investigation was conducted in the research field of Entomology Division at Bangladesh Rice Research Institute (BRRI), Gazipur (23°59′29.3″N and 90°24′25.2″E) during T. Aman season from 2021 to 2024 (Fig. 1).

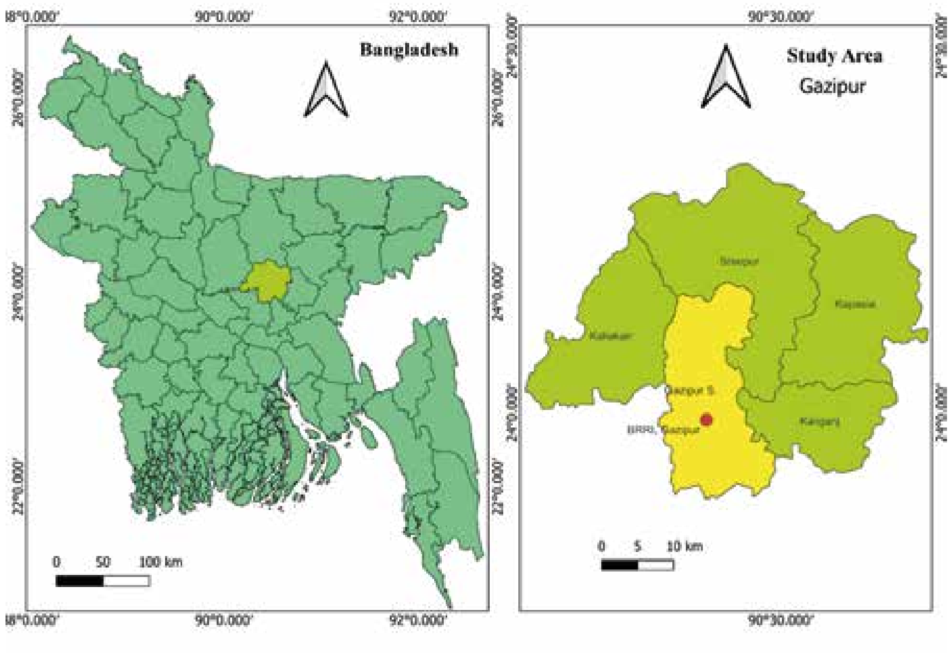

Fig. 1. Location map of study area.

2.2. Treatment, Agronomic management and Application of insecticide

There were two treatments (a) T_1 = Farmers practice (3 times application of insecticide), (b) T_2 = Researcher practice (judicial use of insecticide/ almost insecticide free). The experiment followed a randomized complete block design (RCBD) with three replications. BRRI dhan87 was used during T Aman season in 2021 and 2022, whereas BRRI dhan103 was used in 2023 and 2024. Firstly, seeds were soaked for 24 hours and after germination of the seeds, they were sown on the wet seedbed of BRRI research fields. Twenty-five days old seedlings were transplanted in the main fields. The spacing 20 × 20 cm was maintained between plants and rows, with a 60 cm spacing from one plot to another plot. Individual plot was 15 decimals in size, so one treatment required 45 decimals land. The crop was cultivated following the BRRI recommended fertilizer management package, which included urea, muriate of potash (MoP), triple superphosphate (TSP), zinc sulfate and gypsum, applied at rates of 165, 60, 105, 5 and 61 kg ha^{-1} respectively in both treatments.

The experimental fields were kept weed free by herbicide use and manual hand weeding. Supplementary irrigation was provided as per requirement until flowering stage. In farmers practice (T_1) plots, herbicide was used one time, consequently three times of insecticides applications were done by hand broadcast (granular insecticide) and by spraying with knapsack sprayer (wettable granule and wettable powder). In the T_1 treatment, insecticides were applied three times following standard farmer practices. A granular insecticide, fipronil 3GR @ 10.0 kg/ha, was applied once, while a foliar spray mixture of (chlorantraniliprole + thiamethoxam) 40 WG @ 75.0 g/ha was applied twice at 25-day intervals. The first granular application coincided with the first top dressing of nitrogenous fertilizer (urea), followed by two subsequent foliar applications at 25-day intervals.

The experimental fields T_2 (Research practice plots) were maintained at an even water level to suppress weed growth followed by hand weeding. Rice seedlings were ensured to be free from weed contamination at the time of transplanting. Balanced doses of basal fertilizers were applied, along with split applications of nitrogenous fertilizers, to minimize the incidence of planthopper infestation, bacterial blight, and stem rot diseases. In research practice field (T_2), insecticide applications were deliberately withheld for the first 30 days after transplanting (DAT) to promote the buildup of natural enemies and maintain ecological balance within the rice ecosystem. But in 2022 and 2024, only one-time insecticide (Isoprocarb 75 WP) was applied at 60 DAT in researcher practice (T_2) plots due to high abundance of brown planthopper at economic threshold levels.

2.3. Data Collection

Insect pests and their natural enemies were collected four times by 20 complete hand sweeping. The first sweeping was done before application of insecticide. The 2nd, 3rd and 4th sweeping was done 3 days after application of insecticide in T_1, respectively. Sweeping was also done at similar time frame in T_2. After collection of insect-pests, they were kept in a killing jar with chloroform rinsed cotton inside it for an hour for mortality. Then identification was done by naked eye and helps of stereo-microscope. The number of insect pests and natural enemies obtained from all sweeps in both treatments was counted and recorded separately for comparative analysis. The egg parasitism percentage of brown planthopper, yellow stem borer and larval parasitism of rice leaf folder was calculated by the following formula-

$$\text{Parasitism (\%)} = \frac{\text{Number of Parasitized Eggs or Larvae}}{\text{Total Number of Host or Larvae}} \times 100$$

Egg parasitism was studied using the retrieval method, while larval parasitism was assessed by collecting larvae from the field, which naturally infested.

2.4. Statistical Analysis

The number of insect pests and natural enemies obtained from all sweeps in both treatments was counted and recorded separately for comparative analysis. All data were analyzed separately using analysis of variance (ANOVA) via "doebioresearch" package in R studio software (version2025.09.00 + 387). The Least Significant Difference (LSD) test, with a significance level of 5%, was used to find significant differences between treatment means. Graphical analysis was performed using the "AgroR" package in R studio. The QGIS software (versions 3.22.9) was used to build the study area map.

3. Results

3.1. Status of harmful insects and their natural enemies before insecticide application

The abundance of the brown planthopper (BPH), green leafhopper (GLH), yellow stem borer (YSB), white leafhopper (WLH), short horned grasshopper (SHG), white-backed planthopper (WBPH), long horned grasshopper (LHG), rice leafroller (RLF), rice bug (RB) and rice whorl maggot (RWM) showed statistically non-significant at both farmers practice and researcher practice field (Table 1). Similarly, the prevalence of spider, damsel fly, dragon fly, ladybird beetle, parasitic wasps, green mirid bug and carabid beetle exhibited non-significance at farmers practice and researcher practice (Table 2). Before insecticide application, no significant differences were observed between treatments for pest or natural enemy abundance, indicating comparable initial field conditions. These results indicate that both treatments started with similar pest pressure and natural enemy abundance, providing a uniform baseline for evaluating the effects of insecticide application.

Table 1
Prevalence of insect pests (number per 20 complete sweeps) before insecticide application in both researcher practice and farmers practice fields during T. Aman season from 2021 to 2024.

Treatment	BPH	GLH	YSB	RB	WLH	SHG	RLR	LHG	WBPH	RWM
T_1 = Farmers practice	0.88	3.63	0.88	0.63	2.13	4.13	0.63	1.13	0.88	2.88
T_2 = Researcher practice	1.00	3.50	0.63	0.50	2.00	4.38	0.50	1.25	0.50	2.88
Levels of Significance	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
p-value	0.3	0.7	0.3	0.7	0.3	0.7	0.7	0.6	0.2	0.9

(**Legend:** BPH; brown planthopper; GLH: green leafhopper; YSB: yellow stem borer; RB: rice bug; WLH: white leafhopper; SHG: short horned grasshopper; RLR: rice leaffolder; LHG: long horned grasshopper; WBPH: white backed planthopper; RWM: rice whorl maggot; LSD: least significance difference; CV: coefficient of variation)

Table 2
Prevalence of natural enemies (number per 20 complete sweeps) before insecticide application in both researcher practice and farmers practice fields during T. Aman season from 2021 to 2024.

Treatment	Spider	Dam. fly	Drag. fly	LBB	PW	GMB	CBB
T_1 = Farmers practice	2.00	2.38	1.25	2.25	2.00	2.50	2.38
T_2 = Researcher practice	2.13	2.50	1.38	2.50	1.88	2.63	2.50
Levels of Significance	ns	ns	ns	ns	ns	ns	ns
p-value	0.7	0.7	0.7	0.5	0.7	0.7	0.8

(**Legend:** LBB: ladybird beetle; PW: parasitic wasps; GMB: green mirid bug; CBB: carabid beetle; LSD: least significance difference; CV: coefficient of variation).

3.2. Status of insect pests and their natural enemies in farmers practice (T_1) and researcher practice (T_2) field after 1st application of insecticide

Statistically significant differences were observed in the abundance of GLH, WLH, SHG, YSB, RLR, BPH and WBPH in farmers practice fields (T_1) and researchers practice field (T_2). However, LHG, RB and RWM showed non-significant difference (Table 3). Whereas researcher practice (T_2) demonstrated highest prevalence of these harmful insects compared with farmers practice (T_1) at first application of insecticide in farmers practice fields. The prevalence of natural enemies after 1st applications of insecticide in farmers practice fields showed statistically significant differences (Table 4) and the studied natural enemies (spider, damsel fly, dragon fly, ladybird beetle, parasitic wasps, green mirid bug and carabid beetle) found highest at researcher practice fields.

Table 3

Abundance of insect pests (number per20 complete sweeps) after 1st application of insecticides in farmers practice field (T_1) during T. Aman season from 2021 to 2024.

Treatment	BPH	GLH	YSB	RB	WLH	SHG	RLR	LHG	WBPH	RWM
T_1 = Farmers practice	0.38	1.63 b	0.25 b	0.50	1.00b	2.13 b	1.13 b	0.63	0.36	1.38
T_2 = Researcher practice	0.88	3.88 a	1.00 a	0.63	1.63 a	5.25 a	1.75 a	1.13	0.88	1.50
Levels of Significance	*	***	***	ns	**	***	**	ns	*	ns
LSD	0.41	0.68	0.37	-	0.36	0.64	0.43	-	0.41	-
p-value	0.02	<0.001	<0.001	0.6	0.002	<0.001	0.008	0.06	0.02	0.7

(**Legend:** BPH; brown planthopper; GLH: green leafhopper; YSB: yellow stem borer; RB: rice bug; WLH: white leafhopper; SHG: short horned grasshopper; RLR: rice leaffolder; LHG: long horned grasshopper; WBPH: white backed planthopper; RWM: rice whorl maggot; LSD: least significance difference; CV: coefficient of variation).

Table 4

Abundance of natural enemies (number per 20 complete sweeps) after 1st application of insecticides in farmers practice during T. Aman season from 2021 to 2024.

Treatment	Spider	Damsel fly	Dragon Fly	LBB	PW	GMB	CBB
T_1 = Farmers practice	1.62 b	0.75 b	0.75 b	1.50 b	1.25 b	1.00 b	1.00 b
T_2 = Researcher practice	3.13 a	2.13 a	2.38 a	3.25 a	2.25 a	2.00 a	4.63 a
Levels of Significance	***	***	***	***	***	***	***
LSD	0.41	0.43	0.49	0.50	0.78	0.41	0.64
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

(**Legend:** LBB: ladybird beetle; PW: parasitic wasps; GMB: green mirid bug; CBB: carabid beetle; LSD: least significance difference; CV: coefficient of variation).

3.3. Status of insect pests and their natural enemies in farmers practice (T_1) and researchers practice (T_2) after 2nd application of insecticide

After 2nd time application of insecticide in farmers practice (T_1) field, the abundance of GLH, WLH, SHG, YSB, RB and RWM showed statistically significant differences, whereas researcher practice demonstrated highest prevalence of these harmful insects compared with farmers practice (Table 5). Furthermore, the prevalence of LHG, RLF, BPH and WBPH demonstrated non-significant difference. Moreover, the abundance of natural enemies after 2nd application of insecticide in farmers practice fields (T_1) showed statistically significant differences (Table 6). In contrast, natural enemies (spider, damsel fly, dragon fly, ladybird beetle, parasitic wasps, green mirid bug and carabid beetle) remained significantly higher in researcher-guided plots (T_2) throughout all sampling periods.

Table 5
Abundance of insect pests (number per 20 complete sweeps) after 2nd application of insecticides in farmers practice (T_2) field during T. Aman season from 2021 to 2024.

Treatment	BPH	GLH	YSB	RB	WLH	SHG	RLF	LHG	WBPH	RWM
T_1 = Farmers practice	1.63	4.75	2.00 a	1.38 a	2.25 b	3.88 b	1.75	1.38	1.13	2.38 a
T_2 = Researcher practice	1.13	5.75	1.25 b	0.63 b	3.13 a	5.25 a	1.50	0.88	0.63	1.25 b
Levels of Significance	ns	*	**	*	**	*	ns	ns	ns	**
LSD	-	0.91	27.83	20.00	0.54	1.36	-	-	-	0.59
p-value	0.1	0.03	0.007	0.01	0.004	0.05	0.1	0.06	0.06	0.002

(**Legend:** BPH; brown planthopper; GLH: green leafhopper; YSB: yellow stem borer; RB: rice bug; WLH: white leafhopper; SHG: short horned grasshopper; RLR: rice leaffolder; LHG: long horned grasshopper; WBPH: white backed planthopper; RWM: rice whorl maggot; LSD: least significance difference; CV: coefficient of variation).

Table 6
Abundance of natural enemies (number per 20 complete sweeps) after 2nd application of insecticides in farmers practice (T_1) field during T. Aman season from 2021 to 2024.

Treatment	Spider	Damsel Fly	Dragon Fly	LBB	PW	GMB	CBB
T_1 = Farmers practice	2.13 b	0.75 b	2.00 b	0.88 b	0.63 b	1.00 b	0.75 b
T_2 = Researcher practice	4.13 a	2.63 a	3.00 a	2.38 a	3.00 a	2.00 a	3.75 a
Levels of Significance	***	***	*	***	***	***	***
LSD	0.88	0.68	0.85	0.41	0.54	0.41	0.62
p-value	< 0.001	< 0.001	0.02	< 0.001	< 0.001	< 0.001	< 0.001

(**Legend:** LBB: ladybird beetle; PW: parasitic wasps; GMB: green mirid bug; CBB: carabid beetle; LSD: least significance difference; CV: coefficient of variation).

3.4. Status of insect pests and their natural enemies in farmers practice (T_1) and researchers practice (T_2) field after 3rd application of insecticide

The prevalence of SHG and RLR showed significant differences between farmers practice (insecticide applied fields) and researcher practice field after 3rd application of insecticide in farmers practice (T_1) field. The prevalence of SHG showed highest in researcher practice and RLR showed highest in farmers practice field (Table 7). Moreover, the abundance of others harmful insects (GLH, WLH, LHG, YSB, BPH, WBPH, RB and RWM) showed non-significant differences between T_1 and T_2 (Table 7). The highest prevalence of natural enemies, including spiders, damsel flies, dragonflies, ladybird beetles, parasitic wasps, green mirid bugs, and carabid beetles in the researcher practice plots (T_2). Conversely, natural enemy populations were significantly lower in the farmers' practice plots due to insecticide exposure (Table 8).

Table 7
Abundance of harmful insects (number per 20 complete sweeps) after 3rd application of insecticides in farmers practice field during T Aman season from 2021 to 2024.

Treatment	BPH	GLH	YSB	RB	WLH	SHG	RLR	LHG	WBPH	RWM
T_1 = Farmers practice	1.75	3.12	1.38	0.88	2.50	3.63 b	2.25 a	1.50	1.25	0.75
T_2 = Researcher practice	1.38	3.75	0.88	0.38	2.88	5.25 a	1.25 b	1.38	0.88	0.88
Levels of Significance	ns	ns	ns	ns	ns	**	***	ns	ns	ns
LSD	-	-	-	-	-	1.08	0.41	-	-	-
p-value	0.2	0.2	0.06	0.06	0.5	0.007	< 0.001	0.7	0.08	0.06

(**Legend:** BPH; brown planthopper; GLH: green leafhopper; YSB: yellow stem borer; RB: rice bug; WLH: white leafhopper; SHG: short horned grasshopper; RLR: rice leaffolder; LHG: long horned grasshopper; WBPH: white backed planthopper; RWM: rice whorl maggot; LSD: least significance difference; CV: coefficient of variation).

Table 8
Abundance of natural enemies (number per 20 complete sweeps) after 3rd application of insecticides in farmers practice field during T. Aman season from 2021 to 2024.

Treatment	Spider	Damsel fly	Dragon Fly	LBB	PW	GMB	CBB
T_1 = Farmers practice	2.00 b	1.13 b	1.38 b	0.88 b	0.75 b	0.88 b	1.00 b
T_2 = Researcher practice	4.25 a	2.00 a	3.63 a	2.88 a	2.75 a	2.50 a	3.25 a
Levels of Significance	***	**	***	***	***	**	***
LSD	0.68	0.59	0.76	0.85	0.81	1.06	0.68
p-value	<0.001	0.007	<0.001	<0.001	<0.001	0.006	<0.001

(**Legend:** LBB: ladybird beetle; PW: parasitic wasps; GMB: green mirid bug; CBB: carabid beetle; LSD: least significance difference; CV: coefficient of variation).

3.5. Parasitism of some key insects and grain yield in both insecticide applied and rational insecticide treated plot

The percentage of egg and larval parasitism of some major insects (brown planthopper, rice leaffolder and yellow stem borer) exhibited significant differences between insecticide free (researcher practice) and with four times insecticide applied (farmers practice) fields (Figs. 2, 3, & 4). Egg parasitism percentage of BPH (20.02%), YSB (27.56%) and larval parasitism of RLR (26.78%) showed highest in researcher practice fields (T_2). The average grain yield of researcher practice field (6.23 t ha^{-1}) and prophylactic insecticide applied (6.21 t ha^{-1}) fields exhibited non-significance difference (Fig. 5), indicating that reduced insecticide use did not compromise productivity.

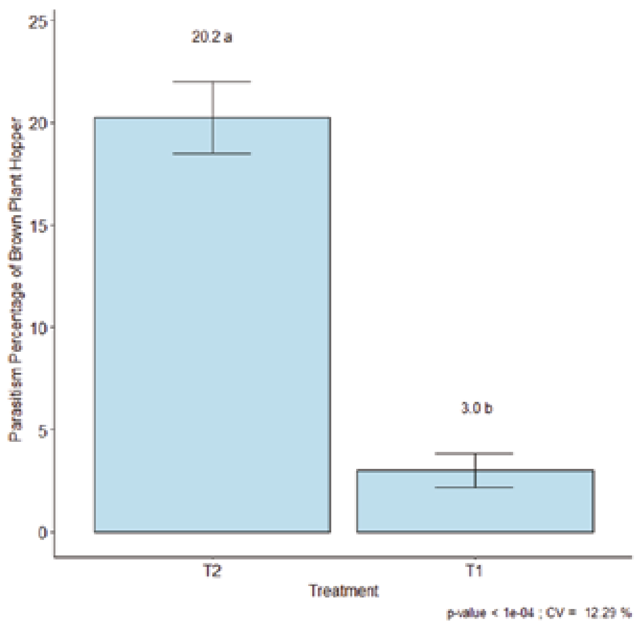

Fig. 2. Egg parasitism percentage of brown plant hopper during T. Aman season from 2021 to 2024.

(**Legend:** T_1 = Farmers practice (prophylactic insecticides applied field), T_2 = Researcher practice (“rational/need based” use of insecticides).

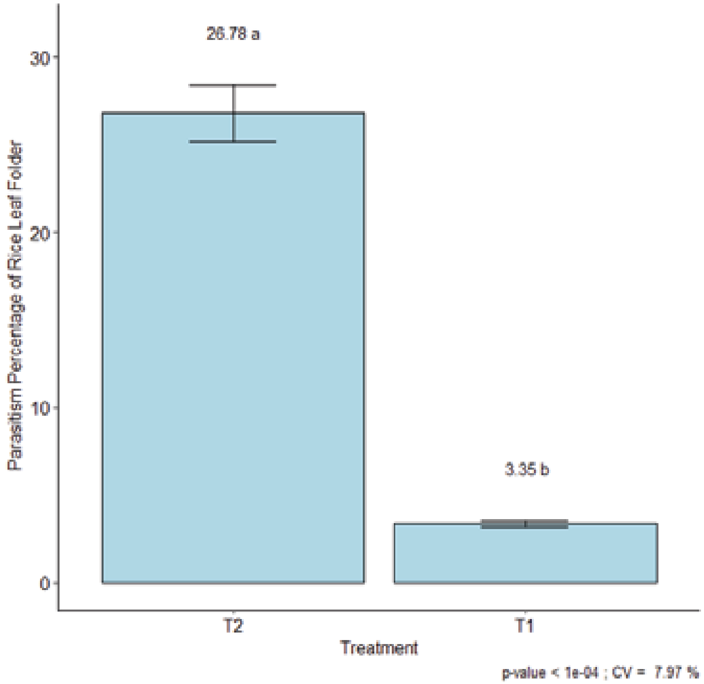

Fig. 3. Larval parasitism percentage of rice leaffolder during T. Aman season from 2021 to 2024.

(**Legend:** T_1 = Farmers practice (prophylactic insecticides applied field), T_2 = Researcher practice ("rational/need based" use of insecticides).

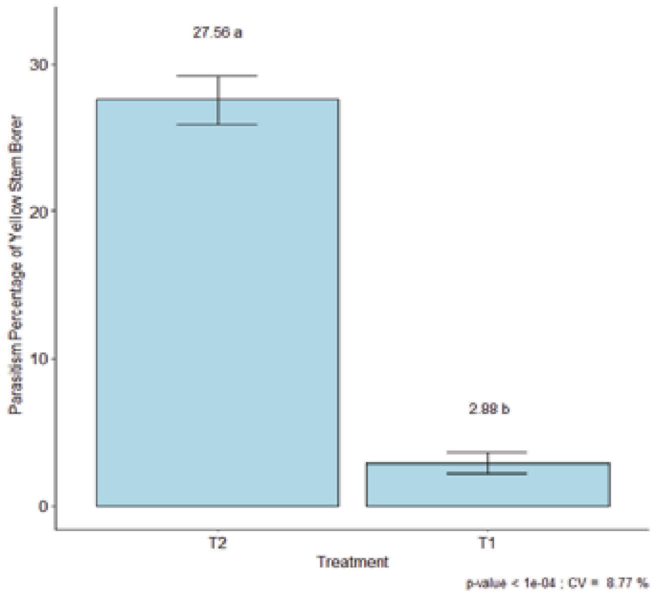

Fig. 4. Egg parasitism percentage of yellow stem borer during T. Aman season from 2021 to 2024.

(**Legend:** T_1 = Farmers practice (prophylactic insecticides applied field), T_2 = Researcher practice ("rational/need based" use of insecticides).

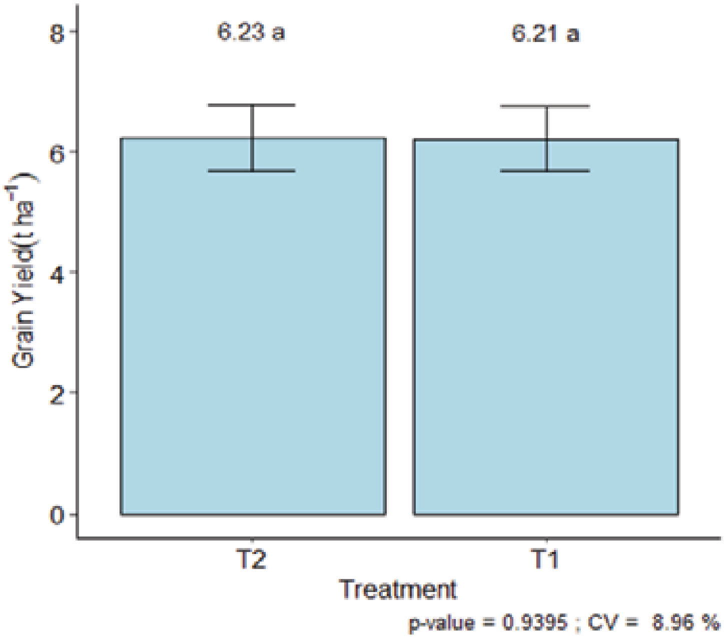

Fig. 5. Average grain yield of different treatments during T. Aman season from 2021 to 2024.

(**Legend:** T_1 = Farmers practice (prophylactic insecticides applied field), T_2 = Researcher practice ("rational/need based" use of insecticides).

4. Discussion

The presence of harmful insects and their natural enemies were observed in rice ecosystems throughout the cultivation process of rice. But the abundance of ups and downs based on the growth stage, availability of foods and disruption of ecosystem by application of insecticides. The natural enemy populations decrease due to indiscriminate applications of insecticides in rice fields which promotes pest outbreaks (Ali et al., 2019; Heong et al., 2015). In present study, we modified insecticide application (rational/need based insecticide application if damage reach to economic threshold level) which promotes biocontrol agents and naturally reduces pests populations and by maintaining no significant losses of rice yields. Prior to any insecticide application of both the treatments, statistically non-significant differences of insect pests and natural enemies in the all studied between the farmers practice (insecticide treatment) and researchers practice (rational use of insecticides) fields establishes a crucial baseline (Table 1 and 2). Our findings indicate that the initial pest and natural enemy pressure was comparable across both treatments at early stage of rice. The balance biodiversity of rice insect pests and their natural enemies observed at early stage of rice without insecticide application, thus helps to pest management naturally (Chaitanya et al., 2024; Chishi et al., 2025; Roy et al., 2024). After application of insecticide in farmers practice, initially observed significant reduction of both harmful and natural enemy. In addition, the results demonstrated that some pest species were more abundant in researcher practice plots after the 1st and 2nd application of insecticides (e.g., GLH, WLH, SHG, YSB, RB, RWM) while other species showed non-significant differences or mixed responses after repeated applications (3rd application) exhibited to specific responses and to temporal dynamics. Insecticide applications can result immediate reductions in susceptible insect pests but also cause trophic cascades (loss of natural enemies) and, in some cases, pesticide-induced pest resurgence via reduced predation, parasitism or sub-lethal stimulation of pest reproduction (Mu et al., 2016; Netra et al., 2024; Ye et al., 2024). Previous studies documented both acute and chronic forms of resurgence in rice planthoppers, mediated by loss of natural enemies, by physiological changes, specifically increased the levels of juvenile hormone and enhancement of fecundity in pest population after exposure to certain pesticides (Gao et al., 2025; Netra et al., 2024).

A consistent pattern was observed across all three insecticide applications (Tables 4, 6, and 8) and was the highest prevalence of natural enemies including spiders, damsel flies, dragonflies, ladybird beetles, parasitic wasps, green mirid bugs, and carabid beetles in the researcher practice plots. Conversely, natural enemy populations were significantly lower in the farmers' practice plots due to insecticide exposure. These findings align with earlier reports showing that insecticides suppress predator and parasitoid species more severely and persistently than they suppress pest populations (Zhang et al., 2017). The continuous high abundance of these predators and parasitoids species in the researcher practice plots highlights the destructive impact of the farmer's insecticide practice on biodiversity and balance ecosystem within the rice field. This phenomenon is well documented in recent studies, where broad-spectrum insecticides applications often cause severe mortality or behavioral disruption in beneficial arthropods, which are crucial for natural pest management (Ali et al., 2019; Bari et al., 2025; Chaitanya et al., 2024; Netra et al., 2024). Moreover, the survived natural enemies face delayed recolonization, and some species required long time to recover after application of insecticides. Moreover, the reduced or absence of the availability of predator or parasitoid species promotes to increase the pest population status even if a short-term knockdown of pests occurs immediately after spray (Ali et al., 2019, 2021; Bari et al., 2025). Natural enemies prey on adults, larvae, and eggs of harmful insects (Roy et al., 2024; Sathischandra et al., 2014). For example, hoppers such as BPH, WBPH, GLH, and SHG serve as prey for green mirid bugs (Islam and Catling, 2012; Roy et al., 2024). The eggs of GLH, SHG, YSB, RLR, BPH, and WBPH are parasitized by parasitic wasps, while ladybird beetles consume nymphs, eggs, and larvae of planthoppers and stem borers (Morshed et al., 2023; Roy et al., 2024). Carabid beetle preys on planthoppers, leafhoppers, stem borers, and root borers (Roy et al., 2024; Sathischandra et al., 2014). Spiders, being highly mobile, quickly colonize rice fields and efficiently predate on numerous pests, including nymphs of hoppers and moths of yellow stem borers and leaf folders (Morshed et al., 2023; Roy et al., 2024). Global estimates suggest that spiders collectively destroy 400–800 million tons of insect pests annually (Nyffeler and Birkhofer, 2017). Resurgence commonly occurs when insecticide application eliminates a greater proportion of natural enemies than target pests, enabling surviving pests to reproduce unchecked, resulting in secondary pest outbreaks (Ali et al., 2019; Bari et al., 2025). The data on parasitism rates strongly supports the effectiveness of biological control in the researcher practice plots. The significantly higher parasitism percentages for brown plant hopper (18.5%), rice leaf folder (29.08%), and yellow stem borer (29.08%) in the researcher practice (Fig. 2, 3, and 4) directly correlates with the highest prevalence of parasitoid, parasitic wasps in these fields (Tables 4, 6, and 8). This is a clear demonstration that insecticide applications severely compromise the natural pest management provided by parasitoids, which are highly susceptible to pesticide exposure (Abdel-Raheem, 2022; Gurr et al., 2003). The higher parasitism rates in the researcher practice plots indicate a robust natural mechanism for natural pest suppression (Ali et al., 2019; Bari et al., 2025). Importantly, grain yield did not differ significantly between the farmers' and researcher practice plots. Similar findings have been reported in previous studies, showing that insecticide-free fields maintain comparable yields to prophylactically sprayed fields (Ali et al., 2019; Bari et al., 2025).

Overall, the results demonstrate that routine insecticide applications disrupt ecological balance, reduce biodiversity, and weaken biological control without providing measurable yield benefits. In contrast, rational insecticide use based on economic threshold levels preserves beneficial arthropods while maintaining effective pest regulation and stable rice production.

5. Conclusion

At the initial stage of rice cultivation, the abundance of harmful insects and their natural enemies was identical across both management practices. However, following insecticide applications, the populations diverged significantly, harmful insects showed varied responses, while natural enemies experienced sharp declines. Field under the researcher practice maintained consistently higher levels of natural enemies, which were sufficient to keep pest populations below damaging levels and protect grain yield. This demonstrates that routine insecticide use in farmers' practice is ecologically detrimental and economically unnecessary, as it disrupts biodiversity without improving yield. These findings reinforce the importance of Integrated Pest Management (IPM) strategies emphasizing conservation of natural enemies, monitoring and threshold-guided management, and the use of selective, reduced-risk interventions when management is necessary. Adoption of such strategies can reduce pesticide dependence, enhance biodiversity, strengthen ecosystem services, and promote the long-term sustainability of rice production systems.

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References

Abdel-Raheem, M. (2022). Effect of Insecticides on Natural-Enemies. In Insecticides - Impact and Benefits of Its Use for Humanity. Intech Open. https://doi.org/10.5772/intechopen.100616

Ali, M. P., Bari, M. N., Haque, S. S., Kabir, M. M. M., Afrin, S., Nowrin, F., Islam, M. S., & Landis, D. A. (2019). Establishing next-generation pest control services in rice fields: eco-agriculture. Scientific Reports, 9(1), 10180. https://doi.org/10.1038/s41598-019-46688-6

Ali, M. P., Nessa, B., Khatun, M., Salam, M. U., & Kabir, M. (2021). A Way Forward to Combat Insect Pest in Rice. Bangladesh Rice Journal, 25(1), 1–22. https://doi.org/10.3329/brj.v25i1.55176

Bari, M., Ahmed, N., Haque, S., Rabbi, M., & Iftekharuddaula, K. (2015). Validation of Integrated Pest Management Practices for Rice Insect in North-west Region of Bangladesh. Bangladesh Rice Journal, 19(1), 17–31. https://doi.org/10.3329/brj.v19i1.25215

Bari, M. N., Haque, S. S., Nowrin, F., Ali, M. P., Kabir, M. M. M., Akter, S., Roy, T. K., & Afrin, S. (2025). Eco-Engineering for Managing Insect Pests in Rice Fields. Bangladesh Rice Journal, 27(1), 49–60. https://doi.org/10.3329/brj.v27i1.77723

Chaitanya, M., Anitha, G., & Mahendra, K. R. (2024). Population dynamics and diversity of pests and natural enemies in various organic rice regimes across different phenological stages in rice. Journal of Biological Control, 351–358. https://doi.org/10.18311/jbc/2024/43096

Chishi, J. A., Neog, P., L, I., Devi, H. S., Waluniba, Sema, T., & Pavan, S. (2025). Diversity of Insect Pests and Their Natural Enemies in Lowland Rice Agroecosystem of Nagaland. Journal of Advances in Biology & Biotechnology, 28(6), 95–105. https://doi.org/10.9734/jabb/2025/v28i62376

Gao, Y., Su, S.-C., Xing, J.-Y., Liu, Z.-Y., Nässel, D. R., Bass, C., Gao, C.-F., & Wu, S.-F. (2025). Pesticide-induced resurgence in brown planthopper is mediated by action on a suite of genes that promote juvenile hormone biosynthesis and female fecundity. eLife 12:RP91774. https://doi.org/10.7554/eLife.91774.2

Gurr, G. M., Wratten, S. D., & Luna, J. M. (2003). Multi-function agricultural biodiversity: pest management and other benefits. Basic and Applied Ecology, 4(2), 107–116. https://doi.org/10.1078/1439-1791-00122

Heong, K. L., Wong, L., & Reyes, J. H. D. (2015). Addressing planthopper threats to Asian rice farming and food security: Fixing Insecticide Misuse. In: Heong, K., Cheng, J., Escalada, M. (eds) Rice Planthoppers. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9535-7_3

Horgan, F. G., Romena, A. M., Bernal, C. C., Almazan, M. L. P., & Ramal, A. F. (2021). Stem borers revisited: Host resistance, tolerance, and vulnerability determine levels of field damage from a complex of Asian rice stemborers. Crop Protection, 142, 105513. https://doi.org/10.1016/j.cropro.2020.105513

Islam, Z., & Catling, D. (2012). Rice Pests of Bangladesh: Their Ecology and Management. University Press Limited, Dhaka. 451

Mu, X.-C., Zhang, W., Wang, L.-X., Zhang, S., Zhang, K., Gao, C.-F., & Wu, S.-F. (2016). Resistance monitoring and cross-resistance patterns of three rice planthoppers, *Nilaparvata lugens*, *Sogatella furcifera* and *Laodelphax striatellus* to *dinotefuran* in China. Pesticide Biochemistry and Physiology, 134, 8–13. https://doi.org/10.1016/j.pestbp.2016.05.004

Netra, H., Hurali, S., Barkeer, S., A, P., R, B. P., & Gowder, S. B. (2024). Reduction of the natural enemy population by deltamethrin and imidacloprid leads to the resurgence of brown plant hoppers (*Nilaparvata lugens*) in rice. Research square. https://doi.org/10.21203/rs.3.rs-4281053/v1

Roy, T. K., Akter, S., Kabir, M. M. M. ., Tonmoy, S. M. M. S., Sharmin, S., Riad, M. A., Rana, M. M., Biswas, M. A., Uddin, A. B. M. A., & Sannal, A. (2025a). Strategic Management of Rice Stem Borer: Evaluating Tobacco Based Alternatives to Reducing Insecticide Dependency. Scientia Agriculturea Bohemica, 56(3), 1–13. https://doi.org/10.7160/sab.2025.560313

Roy, T. K., Biswas, Md. A., Tonmoy, S. M. M. S., Nayeem, A., Hossain, M. M., & Sannal, A. (2025b). Management of Rice Leaf Folder (*Cnaphalocrocis medinalis* Guenée) in Bangladesh: Evaluating the Pesticidal Efficacy of some Botanicals an Eco-Friendly Alternative. Journal of Natural Pesticide Research, 100152. https://doi.org/10.1016/j.napere.2025.100152

Roy, T. K., Kabir, M. M. M., Akter, S., Nayeem, A., Alam, Z., Hasan, M. R., Bari, M. N., & Sannal, A. (2024). Seasonal variations of insect abundance: Correlating growth stage-specific metrics with weather patterns in Rangpur Region, Bangladesh. Heliyon, 10(18), e38121. https://doi.org/10.1016/j.heliyon.2024.e38121

Ye, W.-N., Li, Y., Zhang, Y.-C., Liu, Z.-Y., Song, X.-Y., Pei, X.-G., Wu, S.-F., & Gao, C.-F. (2024). Area-wide survey and monitoring of insecticide resistance in the brown planthopper, *Nilaparvata lugens* (Stål), from 2020 to 2023 in China. Pesticide Biochemistry and Physiology, 205, 106173. https://doi.org/10.1016/j.pestbp.2024.106173

Zhang, H., Ma, D., Qiu, R., Tang, Y., & Du, C. (2017). Non-thermal plasma technology for organic contaminated soil remediation: A review. Chemical Engineering Journal, 313, 157–170. https://doi.org/10.1016/j.cej.2016.12.067

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Half a Century of Rice Research in Bangladesh: A Critical Review on Bibliometric Growth

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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

Bangladesh holds the third largest rice area and the fourth position of its production in the world. The crop alone occupies the three-fourths of annual agricultural land and rice is the synonym of food in Bangladesh. As best of knowledge, no earlier investigation explored the landscape of rice research in Bangladesh through bibliometric approaches. Using the database records of SCOPUS, a meticulous analysis of 1284 articles was conducted spanning the years 1974 to 2022, with specialized software tools viz. VOSviewer, Biblioshiny, and OriginPro. The articles were authored by 3358 scholars from 193 different institutions across 76 countries and disseminated through 424 distinct journals. The annual average growth rate of publications in this domain was found to be 10.76%. Due to elitism of the subject matter, obviously Bangladesh had been the leading country in this field of publications. Among the numerous organizations, Bangladesh Rice Research Institute had achieved the highest rank, followed by Bangladesh Agricultural University and the International Rice Research Institute. The current study has further identified the three most prominent journals in which these articles were published: Field Crops Research, Environmental Science & Technology, and Science of the Total Environment. According to SCOPUS definition, these research publications are clustered into several categories including mainly Agriculture & Biology; Environmental Sciences; Social Sciences; and Biotechnology, Genetic Engineering & Molecular Biology. A cluster analysis of keywords explicitly pointed to 'Rice and Bangladesh' as the focal point of interest within this research area. As a look to the immediate future, forthcoming studies should emphasize the mechanization in rice cultivation, C4 plant type of rice, and premium quality rice for harnessing global market. It is a comprehensive review which may serve as a valuable reference for formulating research priorities to combat global food security challenges

1. Introduction

Rice (*Oryza sativa* L) is the food grain that shaped the cultures, diets, and the economy of billions of Asians. In this vast region, rice is more than food, rice is life. Obviously, it is a staple food for two-thirds of the population in the world (Sen et al., 2020). Rice grain is mostly used as human food, contrasting to other cereals, which are extensively used as feed (Palacpac, 1980). Currently, the total hectarage of global rice planting was recorded at 160 million hectares that represents approximately one-tenth of the cultivated area in the world (Atlas Big, 2023). In the world ranking of rice cultivation, although

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Bangladesh holds the third largest rice area, its position is the fourth in terms of grain production. Compared to Bangladesh, rice area in China, India and Indonesia is less than one-fourth of the cultivated area (Atlas Big, 2023; Kabir et al., 2021; Wikipedia, 2023). For approximately 167 million people in Bangladesh, rice has been contributing 97% of total food grain production (BBS, 2020; FPMU, 2020). Rice is the synonym of food in the country (Shahidullah et al., 2008) and here 'food security' almost entirely depends on 'rice security' (Brolley, 2015). Rice security is not only an economic issue but also an important parameter for determining social and political stability in the country (Nath, 2015). Per capita average intake of rice in the country is about 367 g day^{-1}, which provides nearly 60% of total calories and 50% of total proteins for adults (BBS, 2016). Almost 48% of rural workers are in some way involved in the rice production for their livelihood. Contribution of the rice crop to the value of crop sub-sector is nearby 70% (Mottaleb & Mishra, 2016).

Rice plant has wide adaptability from top of the hill to coast of sea. There are broadly recognized five ecosystems, viz. (a) irrigated ecosystem, (b) rainfed lowland, (c) deepwater, (d) tidal wetland, and (e) upland ecosystem (Khush, 1984). All of the rice growing environments are dispersedly present in Bangladesh. Boro is cultivated during dry winter season in irrigated ecosystem. Transplant Aman represents the rainfed lowland and tidal wetland, whereas Aus is an upland crop and Broadcast Aman represents deep-water rice ecosystem (Nasim et al., 2018). However, with the introduction of modern rice varieties, the association between paddy ecotype and ecosystem is fading (Miah et al., 2004).

Rice research in Bangladesh started its journey in 1910. In course of time, the modern era of rice research in the country started in the mid-sixties (Rahman et al., 2023). Realizing the extraordinary importance of rice in socioeconomic and political aspect, Bangladesh Rice Research Institute (BRRI) was established on the 1st October 1970 (BRRI, 2014). In its initial stage, rice scientists addressed the research for higher grain yield in the favourable ecosystem, however, in course of time, rice research has been facing various global and natural challenges (Kabir et al., 2016). Consequently, the scholars of BRRI as well as other institutions and different universities expanded their activities in the field of variety development on drought tolerance (Brammer, 1987; Torres et al., 2013), flash flood and submergence (Iftekharuddaula et al., 2015; Iftekharuddaula et al., 2016), pest management and disease resistance (Chowdhury et al., 2015; Cork et al., 2005; Howlader & Matin, 1988; Khanam et al., 2016), weed management and allelopathy (Islam & Molla, 2001; Rashid et al., 2012; Salam & Kato-Noguc, 2010; Salam & Kato-Noguchi, 2009), salt stress and salinity management (Al-Forkan et al., 2005; Islam et al., 2016; Lisa et al., 2011), arsenic contamination in soil and rice grain (Abedin et al., 2002; Meharg & Rahman, 2003), global warming and green-house gas emission in the rice land (Ali et al., 2014; Gaihre et al., 2015), integrated rice-fish culture (Frei et al., 2007; Haroon & Pittman, 1997; Mustow, 2002) and food policy and socio-economic aspects of rice cultivation (Bera & Kelley, 1990; Chowdhury et al., 2022). The country is at the reach of food grain sufficiency and the time and human desire raised the demand of quality rice (Kabir et al., 2021). Perceptibly, rice scientists are implementing research on aromatic and premium quality rice (Shahidullah et al., 2011; Shahidullah et al., 2010; Shahidullah et al., 2009), zinc enriched rice (Ara et al., 2019; Mayer et al., 2007), β-carotene enriched golden rice (Biswas et al., 2021; Swamy et al., 2019) and biofortification of rice food (Hotz et al., 2015; Promthai et al., 2009). All of the above-mentioned studies collectively had built a strong foundation for the advancement of rice research of Bangladesh up to the global standard.

Bibliometric analysis is a broad-aspect as well as multidisciplinary research methodology based on computer engineering, database management, and statistical procedures (Chen et al., 2016). It has a difference from 'conventional reviews' and 'meta-analyses', and has many advantages, which includes visual analyses of datasets of contributing authors, journal sources, keywords, institutions, etc.; quantitative cum statistical analyses of the research trend and characteristics of certain topics (Chen et al., 2014; Shahidullah et al., 2024); research into the frontiers and hotspots; and knowledge disseminations and interactions among different disciplines (Lv et al., 2021). In the current years, bibliometric analysis has attained a widespread recognition and application across diverse domains of research (Chen et al., 2014; Shahidullah et al., 2025; Shahidullah et al., 2024). Nevertheless, documentation of rice research in Bangladesh on the basis of bibliometric approaches received a little attension.

The current study aims to provide an inclusive overview of existing academic literature in the connection of rice research in the country, identifying research thrusts, trends as well as emerging research issues, particularly in relation to the alignment of sustainable and nutrient-enriched food production. The specific research query (RQ) includes:

RQ1 : What is the annual progress of scientific documentations on rice research in Bangladesh?

RQ2 : Who are the leading contributors, which are important journals, and which are active institutions for contribution to the documentations?

RQ3 : Which are the articles that make substantial influence in the field of rice research in the country?

RQ4 : Which level of cooperation exist among the institutions and countries engaged in the research, and how the collaborations are helping the research landscape?

RQ5 : What are the emerging research issues, and what trends could be discerned within existing scientific literature on rice?

2. Materials and methods

The SCOPUS dataset has been used as the information source for the analysis in the current study. This study employed broadly two techniques, the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) for a systematic review of articles included in the investigation and the Bibliometric Analysis. On the 1st October 2023, a search had been conducted in the Scopus database, using the search query ((TITLE (rice AND bangladesh) OR ABS (rice AND bangladesh)) AND (LIMIT-TO (LANGUAGE, "English") AND PUBYEAR > 1973 AND PUBYEAR < 2023) AND (LIMIT-TO (DOCTYPE, "ar")) AND (EXCLUDE (PUBSTAGE, "aip")). This query string initially resulted in 2140 documents. We did not limit the starting time of publication documents, however, in fact, it is available from 1974 and not before the year. After excluding all the documents published in 2023 for its incompleteness, the number was downgraded to 2024 (Fig. 1). Then the documents were brought in the limit of English language and journal articles. Then A manual sorting process refined the dataset, discarding the rest of irrelevant articles, finally yielding a concrete set of 1,284 articles. Selected articles were downloaded and then saved in "csv" file format along with complete records of citation data. We opted the SCOPUS database was for its reputation, for maintaining multidimension data selection, indexing standards, confirming reliability and the quality of database. Extensive coverage of SCOPUS, especially within our targeted academic disciplines, particularly was aligned with the research domain. In the present time, this database is rigorously used to accomplish the bibliometric analysis in the scientific investigation (Guerrero-Bote et al., 2021; Hashem et al., 2023; Magadán-Díaz & Rivas-García, 2022; Sau & Nayak, 2022; Sevillano-Jimenez et al., 2023).

We got several basic information from preliminary analysis of the database itself, including authorship of the articles, disciplinary distribution of the documents along with yearly growth rates, journal sources, institutional affiliations as well as countries of origin. The analysis yielded various metrics viz. ranks, frequency, ratios, trends, network analysis, co-authorship, citations, and co-word analysis. Software tools like 'R' with Biblioshiny package (Aria & Cuccurullo, 2017) along with VOSviewer 1.6.19 (the Netherlands Center for Scientific & Technological Research) were employed for in-depth advanced analysis. These are powerful tools that facilitated the mapping of keyword co-occurrence for the identification of fundamental research directions and detection of emerging research hotspots. For more visual representations of the findings, MS Excel 365 & OriginPro 2023b were also used to prepare numerous graphs.

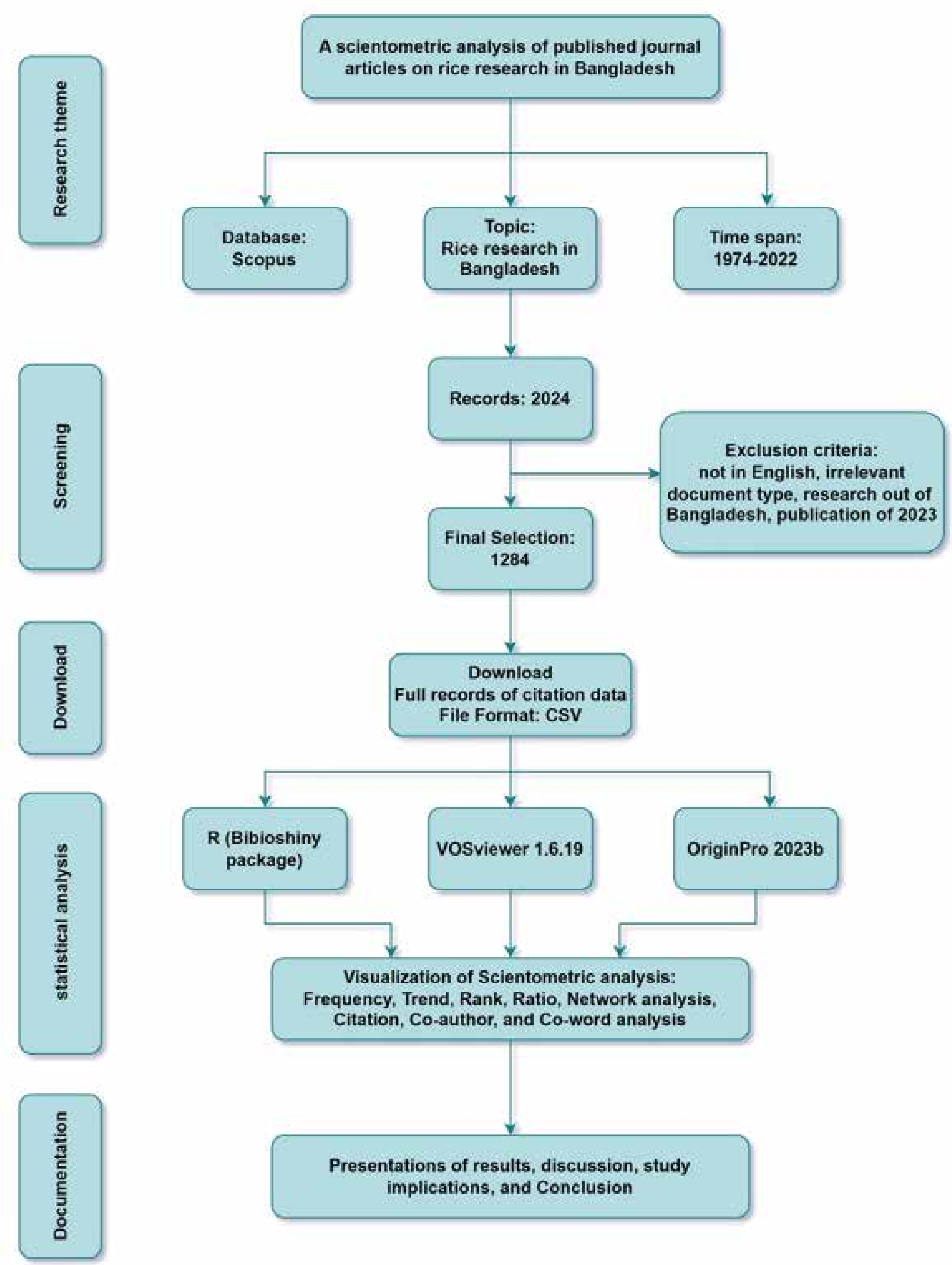

Fig. 1. A flow diagram for bibliometric analysis.

3. Results

3.1. Descriptive statistics of rice research in Bangladesh

Descriptive statistics of the rice research in Bangladesh offer profound intuitions into its scientific as well as practical implications. In the analysis of 1284 documents on rice research in the country, a total of 3358 authors were enlisted. Among them 80 authors had had single-authored articles, contributing to a sum of 108 single-authored publications in the dataset. A research article, the most pioneer in this domain, was published in 1974 (Shahjahan, 1974). A consistent growth in scientific publications at average rate of 10.76% was recorded in the half-a-century time series. The phenomenon signifies the growing scientific interest in Bangladesh rice research, recognizing its importance to address food security and also sustainable intensification. In the total time span, an average number of per document citations stood at 27.95. The growth rate of publications showed a slow increase until 1989, remained fairly stable until 2000, and performed a better growth up to 2022 (Fig. 2). The surge of publications in 2021-22 hints at evolving trends of developments that warrant a continuous attention on future research issues. Moreover, the distribution pattern of the publications has been visually represented in Figure 3, where the publication counting appears as an over number at 1708. This happened due to multi-categoric nature of numerous articles. Within the SCOPUS distribution, 43% of the articles fell under the category of Agricultural and Biological Sciences, 19% in Environmental Sciences, 9% in Social Sciences, 7% in Biochemistry Genetics and Molecular Biology, with the remaining dispersed across six other disciplines. The multidisciplinary involvement in research highlights the needs of holistic approach for understanding complex dynamics in research systems in Bangladesh rice. In sum, the current findings might be helpful for policy formulation, academic enrichment of scholars and students. It might also serve in the practical applications for sustainable agricultural development, reducing ecological impacts, and ensuring food security.

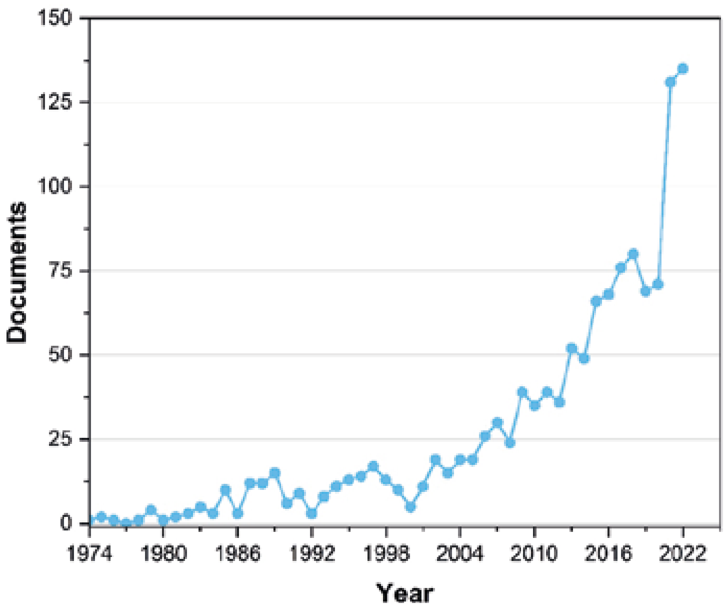

Fig. 2. Periodic distribution trends of publications of rice research in Bangladesh from 1974 to 2022.

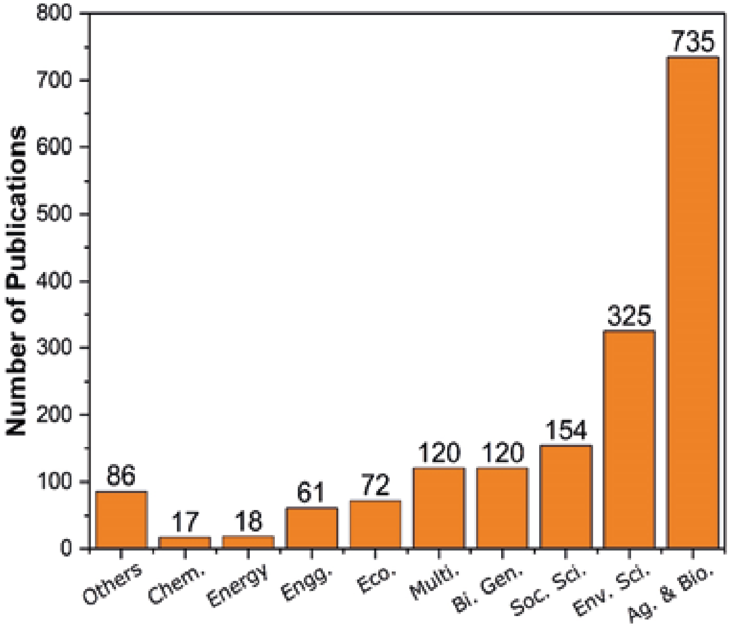

Fig. 3. A distribution pattern of published papers in different categories in rice research of Bangladesh.
Note: Multi. = Multidisciplinary subject, Bi.Gen. = Biotechnology, Genetic Engg. and Molecular Biology.

3.2. Leading contributors, organizations, and countries

Fig. 4 (a-d) illustrates a list of top 10 authors according four distinct criteria. In the viewpoint with number of publications, M.R. Islam from Bangladesh Agricultural University (BAU), appeared as the most creative author was responsible for 38 publications, constituting 2.96% of the total, followed by A.A. Meharg (University of Aberdeen) with 24 and Bell R.W. (Murdoch University) with 21 publications, accounting for 1.87% and 1.63% of total number of scientific articles. In consideration of total citations, A.A. Meharg is the top-ranking author with 4499 citations, while the second most influential author was F.J. Zhao (Rothamsted Research, UK) for 2052 citations. In an assessment method of h-index, A.A. Meharg occupied the highest score of 22 followed by M.R. Islam with scores 19. Norton G.J. (University of Aberdeen) and Bell R.W. both attained an equal score of 15. In the calculation of the g-index, M.R. Islam again achieved the first position with 25 score. AA Meharg ranked in the 2nd position with 24 score followed by Jahiruddin M (BAU) and S Rahman (University of Plymouth) with 19 score. Authorship analysis in this sub-section provides valuable understandings on key contributors in the rice research of Bangladesh. It might be helpful for other researchers to harvest their talents and feasible collaboration for the advancement in sustainable agriculture.

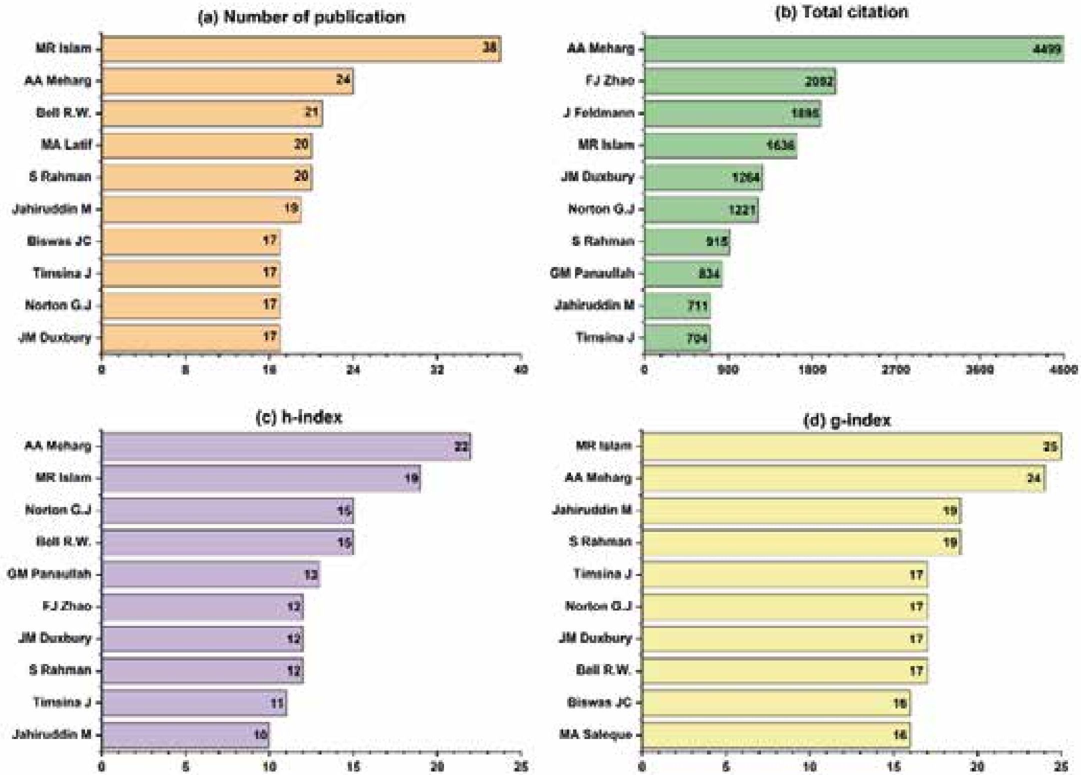

Fig. 4. (a) Authors ranked by number of publications (top 10), (b) Authors ranked by total citations (top 10), (c) Authors ranked by h-index (top 10), (d) Authors ranked by g-index (top 10).

In the compilation of research institutions, Fig. 5(a) presents the list of top ten contributors. The Bangladesh Rice Research Institute (BRRI) stands at the top position with 451 research documents, constituting 35% of the total publications, followed by Bangladesh Agricultural University (BAU) with 280 publications, accounting for 22%. The International Rice Research Institute (IRRI) holds the third position with 208 publications, representing 16% of total. The Bangladesh Agricultural Research Institute (BARI) and the University of Aberdeen jointly holds the 4th position producing 124 publications each, amounting to about 10% contribution individually.

The current review study deals with rice research exclusively in Bangladesh. Obviously, Bangladesh emerged as the foremost contributor, producing 714 research papers. Among those, 436 papers were exclusively produced by Bangladesh itself and the rest were with international collaboration (Fig. 5b). Considering international and inter-institute collaboration, the total count exceeded due to overlap, resulting in a recorded contribution of 56% for Bangladesh. The USA, Australia, United Kingdom and all other countries in the descending order contributed from their part in the publication of the articles. In this list, a notable matter is that the majority of articles were written with international collaboration. The collaboration and research initiatives within Bangladesh and abroad have made a notable impact on the global landscape of sustainable agriculture.

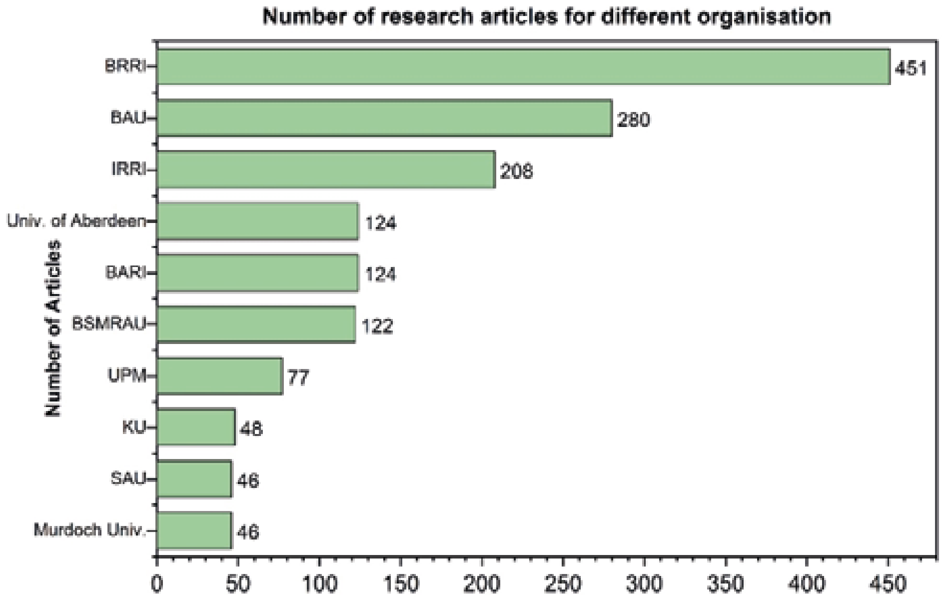

Fig. 5 (a). Ranking of the research entities for the number of publications (top 10).

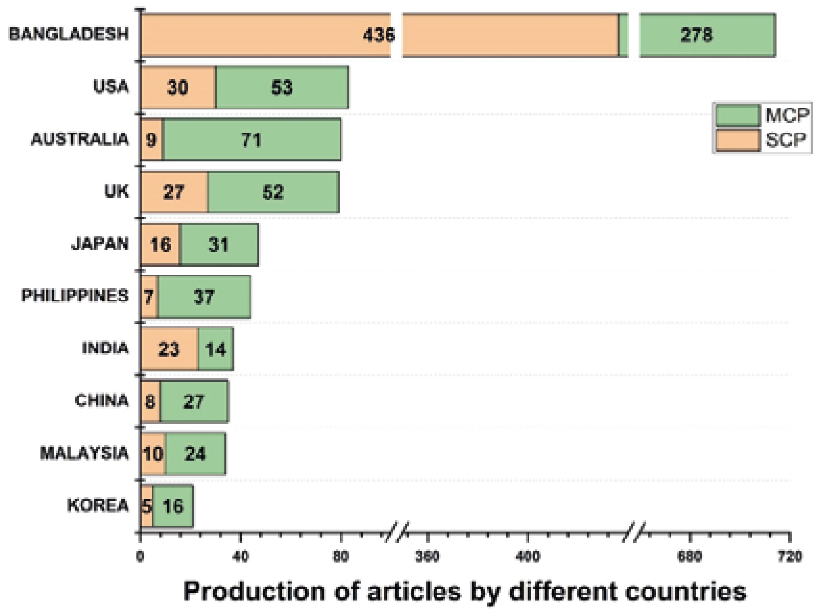

Fig. 5 (b). Ranking of the countries on the basis of number of publications (top 10).
Note: MCP = Multiple country production; SCP = Single country production.

3.3. Most dominant journals

The research articles appeared in 424 journals. Among those sources 15 dominating journals had been found to contain 21% of the publications (Table 1). The highest-ranking Field Crops Research published 41 articles mainly on system research including long-term yield trend of rice (Saleque et al., 2004), rice-wheat system (Adhikari et al., 1999), system of rice intensification (Latif et al., 2005), nitrogen use efficiency and nitrogen budgeting (Hossain et al., 2012; Hossain et al., 2005), tillage system and planting method (Haque et al., 2016; Hossen et al., 2018; Rashid et al., 2018). Environmental Science and Technology produced 29 and Science of the Total Environment published 25 papers covering the area mainly of heavy metal (viz. arsenic, cadmium etc.) contamination in soil and water, uptake and distribution of heavy metals in different parts of rice plants, health risk assessment and its remediation (Abedin et al., 2002; Al Rmalli et al., 2005; Halder et al., 2013; Meharg & Rahman, 2003; Rahman et al., 2006). The fourth top journal, Sustainability (Switzerland) in its 23 papers, had focused the research green-house gas emission, weed regimes and crop diversity (Ahmed et al., 2020; Alam et al., 2021; Haque et al., 2021). Focusing area of the fifth important journal Agroforestry Systems was impact assessment of climate change and various analyses of secondary data source using different simulation models (Matthews et al., 1997; Mottaleb et al., 2015; Sarker et al., 2012). The published papers in Communications in Soil Science and Plant Analysis mainly were on role of macro and micronutrients in paddy soil, nutrient management, farmers' empirical knowledge on nutrient management, organic amendments and soil health (Haque et al., 2019; Haque et al., 2015; Moslehuddin et al., 1999; Paul et al., 2014; Saha et al., 2007; Saleque et al., 1998; Saleque et al., 2004; Saleque et al., 2007). The seventh raking PLOS One produced the documents concentrating on food and nutrition security, demand-supply chain, germplasm analysis (Ara et al., 2019; Islam et al., 2018; Jiang et al., 2021). The next source is Bangladesh Journal of Botany whose publications cover the research area on insect and disease management, soil salinity and heavy metal contamination in soil (Rahman et al., 1970; Shamsi et al., 2003; Ullah et al., 2017). Agricultural Water Management, a journal assigned for specific research area, published 15 articles on assessment of water consumption and irrigation requirements, economic analysis of various irrigation models (Islam et al., 2018; Jensen et al., 1993; Maniruzzaman et al., 2015). The published documents of the journal AMA, Agricultural Mechanization in Asia, Africa and Latin America mainly highlighted the post-harvest technology of rice, also some experiments on field machineries (Basunia & Abe, 2001; Hossen et al., 2013; Islam et al., 2004). There were 14 articles in Plant and Soil where main importance was paid on biofertilizer and toxicity of irrigation water (Abedin et al., 2002; Khan et al., 2009; Mian & Stewart, 1985). Articles of the journal Crop Protection mainly deals with rice nematode diseases, major insect pests and crop loss assessment due to biotic factors (Catling et al., 1987; Datta et al., 2021; Khanam et al., 2016). Agriculture, Ecosystems and Environment published papers in relation to rice-fish, rice-based cropping systems, socio-economic and environmental constraints in rice farming (Hossain et al., 2016; Mustow, 2002; Rahman, 2015). The emphasis of Land Use Policy was on land ownership system, adoption studies on farming enterprises and technologies, analysis of farmers perceptions and risk management of different farming systems (Kabir et al., 2020; Kabir et al., 2017; Rahman & Rahman, 2009). Research on Crops covered several thematic areas viz. planting time, nutrient and weed management, special quality rice (Afrin et al., 2015; Islam et al., 2014; Sarwar et al., 2022).

Table 1
Top journals by number of publications (> 10 publications) on rice research in Bangladesh up to 2022.

Rank	Journal name	Publisher	Number of papers published	Ratio (%)	ACFPY	Area of research
1	*Field Crops Research*	Elsevier B.V.	41	3.19	45.15	System research, soil nitrogen, tillage and planting method
2	*Environmental Science and Technology*	American Chem. Society	29	2.26	171.86	Heavy metal contamination and mitigation
3	*Science of the Total Environment*	Elsevier B.V.	25	1.95	54.12	Heavy metal contamination and health risk assessment
4	*Sustainability (Switzerland)*	MDPI	23	1.79	14.52	Environmental risk, and biotic and abiotic stress
5	*Agricultural Systems*	Elsevier Ltd	19	1.48	42.95	System analysis with statistical models
6	*Communications in Soil Science and Plant Analysis*	Taylor and Francis Inc.	17	1.32	15.06	Fertilizer management in rice based cropping systems
7	*PLOS One*	Public Library of Science	16	1.25	28.31	Germplasm assessment, Food and nutrition security
8	*Bangladesh Journal of Botany*	Bangladesh Bot. Society	16	1.25	3.56	Pest management and disease resistance, and problem soils.
9	*Agricultural Water Management*	Elsevier B.V.	15	1.17	34.13	Water management in rice field
10	*AMA, Agricultural Mechanization in Asia, Africa and Latin America*	Farm Machinery Industrial Research Corp.	15	1.17	4.60	Agricultural Mechanization
11	*Plant and Soil*	Springer Int. Publishing	14	1.09	86.86	Soil microbiology and contaminated water
12	*Crop Protection*	Elsevier Ltd	13	1.01	17.69	Pest management
13	*Agriculture, Ecosystems and Environment*	Elsevier B.V.	11	0.56	35.73	Agro-ecosystem and integrated rice farming
14	*Land Use Policy*	Elsevier Ltd	10	0.78	66.40	Socio-economic studies of farming enterprises
15	*Research on Crops*	Gaurav Publications	10	0.78	0.80	Crop management

Note: ACFPY denotes the average cited frequency per year.

3.4. Most influential documents

Out of 1,284 articles only 19 papers achieved the citation frequency 200 and above (Table 2). Fourteen articles, out 19 most cited articles, reported toxic elements (arsenic and cadmium) in rice. The first and the second most cited articles, which documented the arsenic contamination levels in irrigation water, paddy soil, and rice samples had touched 836 and 628 citations, respectively (Meharg & Rahman, 2003; Meharg et al., 2009). The article reported a wide range of variations over locations, countries and food sources. Discoveries of the analyses encouraged a lot of follower scholars to execute research works to find out the available form of arsenic, its concentration in different water and food sources, its toxicity levels, detrimental effect on health and its mitigation strategies (Polizzotto et al., 2013; Roberts et al., 2010; Zhao et al., 2013). The number three publication is followed by 588 citations. It was a massive laboratory work on molecular genetics of rice germplasm in Bangladesh and other Asian countries (Glaszmann, 1987). Here the germplasms were separated on the basis of genetic makeup into six groups. Genetic variability is a basic pre-requisite for varietal improvement. In fact, this fundamental work is being used as a reference for many investigators (Khan et al., 2017; Parsons et al., 1997; Suh et al., 1997). The 4th, 6th to12th, 14th and 18th highlighted a hotspot research area on arsenic toxicity. In those investigations, the authors surveyed and collected water samples of different sources, samples of rice plants, rice grain, rice husk, rice bran, brown rice, white (polished) rice, parboiled rice, un-parboiled rice, cooked rice and various food items of vegetables and animal sources. After determination of arsenic concentrations, they hypothesized some relationship or linkage among different factors, identified several determinants and proposed various ways to overcome the problems (Abedin et al., 2002; Duxbury et al., 2003; Khan et al., 2017; Meharg et al., 2008; Panaullah et al., 2009; Rahman et al., 2007; Zavala & Duxbury, 2008). The above-mentioned studies received citation in subsequent publications (Fulda et al., 2013; Meharg et al., 2013; Rahman et al., 2014; Zhao et al., 2013). The 5th publication was on the basis of a global survey and laboratory analysis of cadmium concentrations in food samples. From a survey of 12 countries on four continents, Cd levels in rice grain were the highest in Bangladesh and Sri Lanka, with both these countries correspondingly having high per capita rice intakes (Meharg et al., 2013). After arsenic, cadmium also attracted the researchers for burning health hazard issues, and the work was cited 355 times in scientific literature (Shahriar et al., 2022; Shi et al., 2020). The third most cited article (Glaszmann, 1987), which had

588 citations, was on molecular genetics of rice germplasm in Bangladesh and other Asian countries were separated the germplasms on the basis of genetic makeup into six groups. Genetic variability is a basic pre-requisite for varietal improvement. Several investigators (Khan et al., 2017; Parsons et al., 1997; Saleque et al., 2004; Suh et al., 1997) cited fundamental work. The 13th most cited paper, which described the cost analysis and output efficiency of rice farming, obtained 246 citations. Allocative inefficiency was low due to over-use of labour forces, deviated rates of input use and inferior market facility (Coelli et al., 2002). Cost minimization is a crucial issue in successful rice production and food security. This type of research is a continuous thrust, and that is why the successor scholars cited the reference (Ladha et al., 2016; Rahman, 2003, 2009). The 15th ranking cited paper offered attention on a very serious issue of climate change concerning the use of groundwater for rice cultivation in dry season (Shahid, 2011). The groundwater level is depleted in dry season and it is recharged in monsoon in Bangladesh. However, over exploitation of groundwater than its annual recharge is a serious threat for environment, agriculture and future population. Localized monitoring and evaluation of groundwater status should get special priority. This perception encouraged the researchers to continue groundwater research and they followed the above-mentioned reference (Acharjee et al., 2017; Acharjee et al., 2017; Ahmed et al., 2017). Finally, the 19th article has focused a different dimension of research that is invariably important for the nation at a glance. It discussed the negative impact of land fragmentation and current resource ownership system (Rahman & Rahman, 2009). Better policy adoption may overcome the current constraints. Many scientists have executed various socio-economic investigations concerning rice production, technology adoption and farmers perception (Alam et al., 2014; Roy & Chan, 2015; Roy et al., 2013).

Table 2

Top published papers on rice research in Bangladesh ranked by citations (>200 citations) (up to 1st October 2023).

Title of the research article	CF	ACFPY	Key findings	Ref.	Journal
1. Arsenic contamination of Bangladesh paddy field soils: Implications for rice contribution to arsenic consumption	836	39.81	Rice cultivated with arsenic contaminated groundwater had high arsenic concentrations	(Meharg & Rahman, 2003)	EST
2. Geographical variation in total and inorganic arsenic content of polished (white) rice	628	41.87	Total arsenic content of rice varied significantly across different countries	(Meharg *et al.*, 2009)	EST
3. Isozymes and classification of Asian rice varieties	588	15.89	Provide insights into the isozymes and classification of Asian rice varieties	(Glaszmann, 1987)	TAG
4. Arsenic accumulation and metabolism in rice (Oryza sativa L.)	525	25.00	Emphasize the importance of the factors that influence arsenic accumulation and metabolism	(Abedin, Cresser, *et al.*, 2002)	EST
5. Variation in rice cadmium related to human exposure	355	32.27	Rice is a significant source of cadmium in the human diet	(Meharg *et al.*, 2013)	EST
6. Arsenic concentrations in rice, vegetables, and fish in Bangladesh: A preliminary study	350	17.50	Rice plants, especially the roots, had significantly higher levels of arsenic	(Das *et al.*, 2004)	EI
7. Speciation and localization of arsenic in white and brown rice grains	303	18.94	Arsenic was localized at surface in brown rice whereas it was dispersed throughout the kernel in white rice	(Meharg *et al.*, 2008)	EST
8. Arsenic uptake and accumulation in rice (Oryza sativa L.) irrigated with contaminated water	302	13.73	Arsenic concentrations in all plant parts increased with increasing arsenate absorption in irrigation water	(Abedin, Cotter-Howells, & Meharg, 2002)	PS
9. Arsenic in rice: I. Estimating normal levels of total arsenic in rice grain	257	16.06	Arsenic concentrations in rice from the U.S. and Europe were significantly higher than in Asia	(Zavala & Duxbury, 2008)	EST
10. Accumulation of arsenic in tissues of rice plant (Oryza sativa L.) and its distribution in fractions of rice grain	254	14.94	Arsenic content was higher in non-parboiled rice grain than that of parboiled rice	(Rahman *et al.*, 2007)	Chem
11. Groundwater dynamics and arsenic contamination in Bangladesh	250	13.89	Groundwater flow is dynamic, flushing the aquifer from decades to a century	(Harvey *et al.*, 2006)	CG
12. Arsenic toxicity to rice (Oryza sativa L.) in Bangladesh	248	16.53	Arsenic toxicity poses a significant threat to rice cultivation in Bangladesh	(Panaullah *et al.*, 2009)	PS
13. Technical, allocative, cost and scale efficiencies in Bangladesh rice cultivation: A non-parametric approach	246	11.18	Rice farms in Bangladesh have low levels of efficiencies	(Coelli *et al.*, 2002)	JAE
14. Effect of arsenic on photosynthesis, growth and yield of five widely cultivated rice (Oryza sativa L.) varieties in Bangladesh	228	13.41	Increasing soil arsenic concentrations led to a significant decrease in growth and yield of rice	(Azizur Rahman *et al.*, 2007)	Chem
15. Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh	216	16.62	Increase in daily water use for irrigation, potentially worsening groundwater scarcity	(Shahid, 2011)	CC
16. Redox-controlled changes in cadmium solubility and solid-phase speciation in a paddy soil as affected by reducible sulfate and copper	215	19.55	In multi-metal contaminated paddy soils Cd may remain labile, which enhances the risk for Cd transfer into rice	(Fulda *et al.*, 2013)	EST
17. Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation	212	7.85	Increased CO_2 level was found to increase grain yields	(Matthews *et al.*, 1997)	AS
18. Food chain aspects of arsenic contamination in Bangladesh: Effects on quality and productivity of rice	212	10.10	Rice yields and grain arsenic concentrations were higher in the winter season due to the greater use of groundwater for irrigation	(Duxbury *et al.*, 2003)	JESH
19. Impact of land fragmentation and resource ownership on productivity and efficiency: The case of rice producers in Bangladesh	204	13.60	Land fragmentation reduces rice output while ownership of key resources increases efficiency	(Rahman & Rahman, 2009)	LUP

Note: EST = Environmental Science and Technology; TAG = Theoretical and Applied Genetics; EI = Environment International; PS = Plant and Soil; Chem = Chemosphere; CG = Chemical Geology; JAE = Journal of Agricultural Economics; CC= Climatic Change; AS= Agricultural Systems; JESH = Journal of Environmental Science and Health; LUP= Land Use Policy; CF = Cited frequency, ACFPY = Average cited frequency per year.

3.5. Collaboration among the countries and organizations

Seventy-six countries participated to produce 1284 publications on rice research in Bangladesh, forming a sufficient cross-country co-authorship network. Among those, 38 countries, meeting the thresh-hold level of 5 documents, were used in the visualization of network map shaped by VOSviewer software (Fig. 6a). The countries are found to be stratified in this network map into six separate clusters. Each cluster is represented by a unique colour code. The magnitude of individual sphere within the map resembles the number of research articles belonging to each country, whereas the proximity of nations within clusters indicates the strength of collaboration. Among the clusters, the most dominant one is denoted by blue color, encompassing six countries, including Bangladesh, Australia, South Africa, Switzerland, Belgium and Samoa. The analytical results and the network map visualized the total link strength of individual country. The highest link strength was 56466 for Bangladesh, followed by Australia with 20095, USA with 20048 and UK with 13807. Pattern of cluster formation highlights a synergistic sharing in research interests of countries, exchange of knowledge and global-scale collaboration. As a whole, this collaborative network system might enrich the holistic thoughts of sustainable development in agriculture. The cooperative spirit would be effective to address the challenges in world food security.

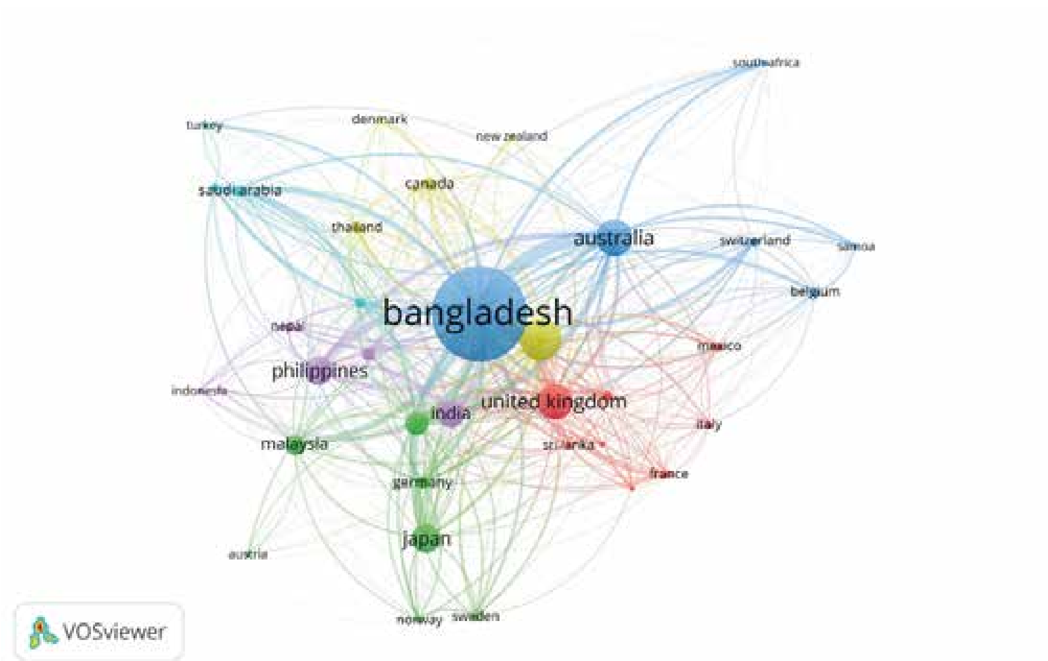

Fig. 6 (a). Collaboration network among the countries for the rice research in Bangladesh.

One hundred and ninety-three institutions contributed to produce 1284 research articles in the rice research of Bangladesh. A VOSviewer generated network map classified these organizations into seven discrete clusters. Each of the cluster is represented by a unique colour, reflecting their collaborative associations (Fig. 6b). Connections between the organizations are denoted by lines. Thickness of the lines indicated the strength of cooperation. Remarkably, the largest number of research institutions are predominantly situated in Bangladesh. In a sum, 43 in-country research entities are involved in its national rice research stream. Extensive collaboration among research establishments suggests the global commitment to advance knowledge sharing in this field. Clustering pattern and interconnectivity of institutions underscore the multidimensional as well as cooperative nature of research in this ground. Such collaborative approaches might enrich agricultural sciences and be helpful for the promotion of effective practices, ultimately supporting global food security cum overall agriculture.

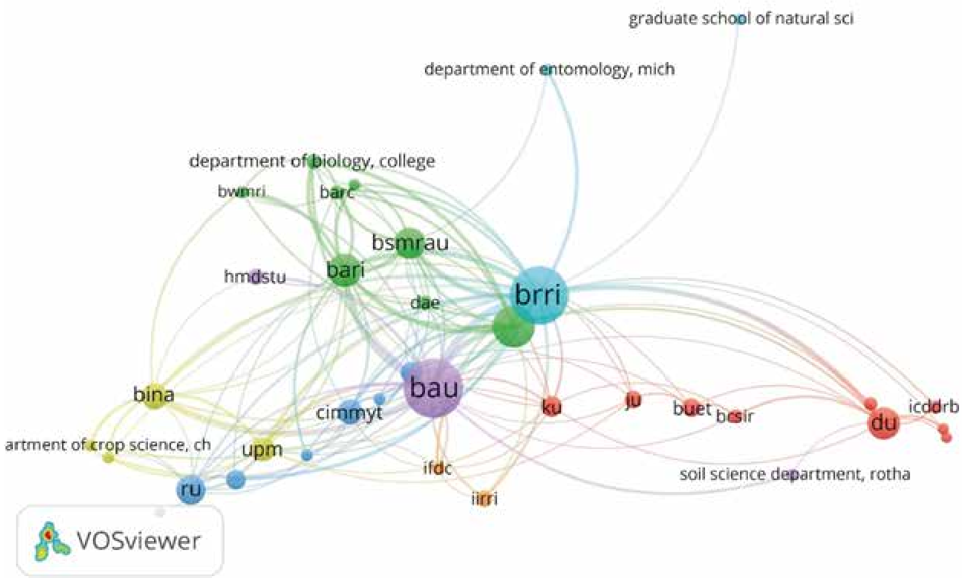

Fig. 6 (b). Collaboration network among the institutes for the rice research in Bangladesh.
BRRI = Bangladesh Rice Res. Inst.; BARI = Bangladesh Agric. Res. Inst.; BAU = Bangladesh Agric. Univ.; BSMRAU = Bangabandhu...Agric. Univ.; BINA = Bangladesh Inst. Nuclear Agric.; BARC = Bangladesh Agric. Res. Council; BWMRI = Bangladesh Wheat and Maize Res. Inst.; CIMMYT = Int. Centre for Maize and Wheat Improvement; DU = Dhaka University; ICDDRB = Int. Centre for Diarrheal Disease Res., Bangladesh; UPM = Universiti Putra Malaysia.

3.6. Collaboration among the countries and organizations

Seventy-six countries participated to produce 1284 publications on rice research in Bangladesh, forming a sufficient cross-country co-authorship network. Among those, 38 countries, meeting the thresh-hold level of 5 documents, were used in the visualization of network map shaped by VOSviewer software (Fig. 6a). The countries are found to be stratified in this network map into six separate clusters. Each cluster is represented by a unique colour code. The magnitude of individual sphere within the map resembles the number of research articles belonging to each country, whereas the proximity of nations within clusters indicates the strength of collaboration. Among the clusters, the most dominant one is denoted by blue color, encompassing six countries, including Bangladesh, Australia, South Africa, Switzerland, Belgium and Samoa. The analytical results and the network map visualized the total link strength of individual country. The highest link strength was 56466 for Bangladesh, followed by Australia with 20095, USA with 20048 and UK with 13807. Pattern of cluster formation highlights a synergistic sharing in research interests of countries, exchange of knowledge and global-scale collaboration. As a whole, this collaborative network system might enrich the holistic thoughts of sustainable development in agriculture. The cooperative spirit would be effective to address the challenges in world food security.

Table 3
Main keywords used in rice research of Bangladesh in different periods.

Period	Main keywords (frequency)
1974 – 1983	Bangladesh (2), rice (2)
1984 – 1993	Bangladesh (28), developing country (10), rice production (9), rice (7), agricultural practice (4), grain (3), water management (3), high yielding variety (2), credit (2), irrigation (2), price stabilization (2), food production (2), higher plant (2), employment (2), technology adoption (2)
1994 – 2003	Bangladesh (65), rice (39), *Oryza sativa* (32), article (16), developing country (12), nonhuman (12), agriculture (9), *Triticum aestivum* (9); rice production (7), crop production (7), arsenic (7), crop yield (6), yield (6), productivity (6), irrigation (6), modelling approach (5), rice cropping (5), Asia (5), crops (5), environmental monitoring (5), plant growth (5), animalia (5)
2004 – 2013	Bangladesh (190), rice (155), *Oryza sativa* (89), article (79), Asia (78), South Asia (77), Eurasia (77), arsenic (67), soil (59), paddy field (45), groundwater (43), irrigation (39), soil pollution (35), crop yield (33), nonhuman (30), crop production (29), *Triticum aestivum* (26), food contamination (26), controlled study (26), water supply (25), water pollutants (24), crops (23), soil pollutants (23), cultivation (22), agriculture (22), groundwater pollution (21), bioaccumulation (21), concentration (35), grain (19), irrigation system (19), food security (18), cultivar (18), environmental monitoring (18), soil analysis (18), animalia (16), priority journal (15)
2014 – 2022	Bangladesh (348), rice (245), human (105), article (96), crop production (84), *Oryza* (76), crop yield (70), climate change (65), soil (56), agriculture (55), nonhuman (51), irrigation (48), fertilizer (48), food security (45), arsenic (45), controlled study (42), risk assessment (41), crops (39), paddy field (37), cultivation (37), *Oryza sativa* (34), food supply (34), cropping practice (33), chemistry (33), groundwater (29), water management (29), concentration (29), irrigation system (28), genetics (27), *Triticum aestivum* (27), wheat (27), fertilizer (48), coastal zone (25), sustainability (25), metabolism (24), salinity (24), farming system (24), health risk (23), food contamination (22), environmental monitoring (22), agricultural land (21), grain (21), procedures (21), profitability (21), agricultural management (21), female (21), drought (20), adaptive management (20), soil pollution (20), soil pollutants (20)

3.7. Keywords co-occurrence and cluster analysis

From a robust series of keyword, only 85 met the thresh-hold level of frequency 6. An inclusive analysis of these keywords in the field of rice research in Bangladesh revealed their categories into 10 discrete clusters summarized in Table 4. The 1st cluster mainly included the analysis of rice germplasms, grain yield of special quality rice, weed management, molecular genetics, and encompassed a total of 14 keywords. Within this cluster, 'rice' emerged as the most frequently occurring keyword, with a notable frequency of 196 and an average citation score of 37.06. It was followed by '*Oryza sativa*,' which exhibited a frequency of 30 and an average citation score of 30.32. The 2nd cluster placed a dense emphasis on salt tolerant rice, adoption and profitability of hybrid rice, global warming and irrigation method, incorporating 11 keywords. Notably, 'agriculture' took the lead in this cluster, boasting an average citation score of 36.76, while 'salinity' garnered a substantial average citation score of 17.79. In the 3rd cluster, the focus shifted towards rice-based integrated farming systems, soil fertility, and yield gap, encompassing 11 keywords. 'Wheat' emerged as the most prominent keyword in this research category, having an average citation score of 32.19, followed by 'productivity' with that score of 31.20. The 4th cluster was dedicated to the evaluation of water source and irrigation management in Boro rice, ecofriendly conservation agriculture and profitable cropping systems, comprising 11 keywords. Within this cluster, 'groundwater' secured the top position with a citation score of 62.26, closely trailed by 'irrigation' with a significant citation score of 36.47. The 5th cluster revolved around integrated rice-fish farming and socio-economic analysis of different technologies. This cluster comprised nine keywords, with 'Bangladesh' and 'technical efficiency' leading the way, boasting average citation scores of 29.70 and 15.64, respectively. The 6th cluster spotlighted research activities related to investigation of heavy metal contamination in rice plants and food chain, incorporating eight keywords. Within this cluster, 'arsenic' and 'soil' held dominance, with citation scores of 84.83 and 55.53, respectively. In the 7th cluster, the keywords were dominated by 'climate change' and Sustainability with citation scores of 28.66 and 20.41, respectively. In this domain main thrust was on the suitability assessment of farming system technologies in environmental stresses. The 8th cluster possessed seven keywords led by 'deepwater rice' with 11.15 citation scores and 'water management' with 20.31. It mainly discussed on physiology and ecosystem of deepwater rice, and mineral nutrition of rice plants. The 9th cluster had had four keywords and addressed the health risk of heavy metals in food stuffs. Finally, the 10th and last cluster, consisting of only two keywords, underscored the significance the issue of food security and poverty.

Table 4
Top journals by number of publications (> 10 publications) on rice research in Bangladesh up to 2022.

Cluster	No. of keywords	Terms (frequency and average citation score)
1#	14	Rice (196, 37.06); *Oryza sativa* L. (30, 30.32); Genetic diversity (13; 13.54); Grain yield (11, 6.73); Paddy soil (11, 33.73); Aromatic rice (7, 7.86); Aus (7, 21.00); Weed management (7, 14.71); Allelopathy (6, 8.67); Germination (6, 36.67); Landraces (6, 16.33); Resistance (6, 8.50); Screening (6, 12.83); SSR markers (6, 3.83)
2#	11	Agriculture (29, 36.76); Salinity (19, 17.79); South Asia (14, 59.43); Hybrid rice (10, 16.50); Profitability (9, 17.22); Alternate wetting and drying (7, 41.57); India (7, 23.86); Adoption (6, 13.33); Greenhouse gas emissions (6, 43.00); Methane (6, 24.33); Seasonality (6, 24.17)
3#	11	Wheat (16, 32.19); Productivity (15, 31.20); Rice yield (15, 25.80); Maize (9, 28.89); Panel data (8, 19.75) Rice straw (8, 14.38); Soil fertility (8, 19.88); Yield gap (8, 40.38); Cropping pattern (7, 6.86); Mungbean (6, 7.00); T. Aman rice (6, 13.17)
4#	11	Irrigation (36, 36.47); Boro rice (29, 11.17); Groundwater (19, 62.26); Water productivity (12, 21.50); Remote sensing (11, 32.64); Conservation agriculture (8, 33.88); Nitrogen use efficiency (8, 23.38); Temperature (8, 7.50); Carbon sequestration (7, 12.57); Cropping systems (7, 4.86); Economics (6, 15.17)
5#	9	Bangladesh (277, 29.70); Technical efficiency (14, 15.64); Rice production (11, 29.73); Efficiency (10, 7.30); Farmer (7, 20.29); Data envelopment analysis (6, 14.17); Fish (6, 37.00); Rice farmers (6, 15.83); Stochastic production frontier (6, 51.67)
6#	8	Arsenic (68, 55.53); Yield (33, 22.70); Soil (12, 84.83); Cadmium (9, 41.11); Water (9, 28.56); Food (7, 127.43); Diet (6, 48.50); Growth (6, 61.67)
7#	7	Climate change (61, 28.66); Sustainability (22, 20.41); Adaptation (20, 39.25) Drought (13, 31.69); Rice farming (11, 26.18); Cropping system (8, 16.88); Coastal zone (6, 29.33)
8#	7	Deepwater rice (13, 11.15); Water management (13, 20.31); Zinc (10, 13.50); Phosphorus (8, 37.88) Nitrogen (7, 25.14); *Oryza sativa* L. (6, 24.33); Regeneration (6, 8.33)
9#	4	Health risk (9, 36.78); Heavy metals (8, 64.38); Cereals (7, 30.71); Dietary intake (6, 38.50)
10#	2	Food security (44, 32.64); Poverty (6, 9.33)

Note: Only the words with frequency > 6 were considered in the cluster analysis.

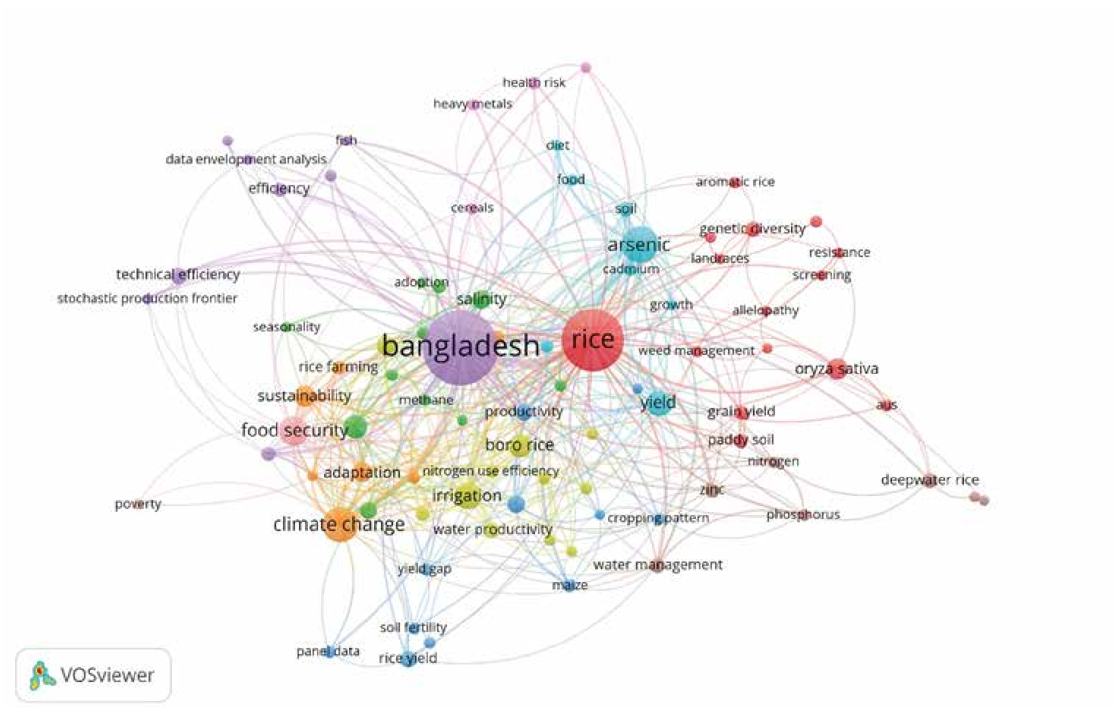

Fig. 7. Co-occurrence network of keywords in rice research of Bangladesh. Each node represents a keyword, with node size indicating frequency. Links between nodes signify co-occurrence, with thicker lines denoting more frequent associations.

3.8. Impact of rice research on socio-economics in Bangladesh

In the current investigation, a series of significant impact of rice research in Bangladesh had been perceived. At a glance, it is clear that, technological progress has helped the country to achieve self-sufficiency in rice production in 2001 from import-dependence, despite doubling of population since its independence in 1971 (Hossain et al., 2006). However, this success story is an accumulation of very specific numerous research fields. Some instances are cited here. A vast area of Bangladesh is vulnerable to flash flood. Submergence tolerant gene has been introgressed in a mega variety BR11. This new genotype offered a yield advantage of 1 to 3 t/ha, depending upon the duration of submergence. Due to their excellent performance in farmers' fields, it is opined that it has the potential to usher a second green revolution in the flood-prone rainfed rice areas (Singh et al., 2013). Short duration, early maturing transplanted Aman varieties efficiently mitigated acute food shortage in northern part of Bangladesh. In addition, it facilitated the timely establishment of the succeeding winter crop which is crucially related to rural employment (Rahman et al., 2018). Research on mechanization in rice cultivation also has significant contribution. Mechanical transplanting along with urea fertilizer deep placement in wet land rice establishment proved 30% urea saving and higher benefit-cost ratio (Hossen et al., 2019). Obviously, urea saving technology is not only an economic issue, but also it is helpful for the reduction of greenhouse gas emission. Boro rice cultivation in Bangladesh is exclusively dependent on groundwater. This valuable resource is declining in an alarming rate. So, the rice scientists developed alternate wetting and drying (AWD) technology that can save up to 40% of irrigation water (Uddin & Dhar, 2020). To meet up the demand of animal protein the scholars have offered integrated rice-fish production technology (Frei et al., 2007; Haroon & Pittman, 1997; Mustow, 2002). Sufficient level of different micronutrients viz. zinc, iron, beta carotene is a pre-requisite for balanced diet. For the alleviation of nutrition deficiency, several rice varieties and technologies are developed (Ara et al., 2019; Biswas et al., 2021; Mayer et al., 2007; Promthai et al., 2009; Swamy et al., 2019).

4. Discussion

Rice, with its extraordinary ecological adaptability (Datta & Surajit, 1981; Moomaw & Vergara, 1964; Nasim et al., 2018), dominates Bangladesh not only as the staple food (Brolley, 2015; Shahidullah et al., 2008) but also as a pillar of social stability, culture, and politics (Ahmed & Zeitlin, 1994; Nath, 2015). Beyond food security, the expanding industrial uses of rice husk, powder, and bran (Abedin & Das, 2014; Ahiduzzaman & Islam, 2016; Haque & Chowdhury, 1994; Islam et al., 1994; Reza et al., 2015; Sumy et al., 2012) highlight untapped opportunities for value addition that remain weakly connected to research and policy. Bangladesh's shift from a "Bottomless Basket" to a food-surplus nation (LaFranchi, 2015; Rahman et al., 2023) illustrates the transformative power of rice science. Yet the slow start of research output- initially focused on post-harvest loss in the 1970s (Shahjahan, 1974), the publication number has amplified and still now it is increasing. These findings showed that rice research in the country had received increasing attention from scholars due to national and global level food security challenges. Increasing food demand for the rising population in developing countries might push scholars for rice research to advance science (Nath, 2015).

Regarding individual country contributions, Bangladesh understandably holds the leading position in rice research. While early initiatives date back to 1910, the modern trajectory of rice research and development truly gained momentum with the institutional foundation set during the 1960s and 1970s (BRRI, 2014; Rahman et al., 2023). Establishment of key institutions such as Bangladesh Agricultural University and Bangladesh Rice Research Institute marked turning points, not merely as academic hubs but as catalysts for capacity building and innovation in the field. The expansion of research across additional universities with agricultural programs reflects a gradual diversification, yet the progress has remained uneven across institutions. Government support for academic career advancement and improved research environments has been decisive; however, this reliance on state-driven initiatives also underscores the vulnerability of research growth to shifting policy priorities. Investments in engineering and mechanization (Hossen et al., 2018), and later in genetic research (Khan et al., 2017), have enabled technological breakthroughs, though the sustainability of such advancements often hinges on continued funding and institutional commitment. Notably, external projects such as the Agricultural Research Management Project, PETRRA, and those supported by the Bill and Melinda Gates Foundation have played pivotal roles in strengthening laboratory infrastructure, scientist training, and field experimentation. While these contributions accelerated progress, they also highlight a dependence on project-based funding, raising concerns about long-term autonomy and consistency in research agendas.

Effective collaboration and communication among institutions stand as crucial pillars for improving research quality and developing skilled manpower (Edmondson & Harvey, 2018; Hsiao et al., 2012; Kezar, 2006). Authorship and institutional analyses reveal a few prolific scholars and institutions such as BRRI and BAU dominate output from the collaboration largely within national boundaries. Limited cross-country connectivity indicates that much more expansive and inclusive collaboration is both possible and necessary. The analysis further reveals an imbalance between domestic and international partnerships, where certain institutions, such as the Bangladesh Council for Scientific and Industrial Research (BCSIR), display notable weaknesses in both local and global linkages. Addressing these shortcomings may require policy-level incentives that encourage wider participation and joint initiatives. Moreover, geographical proximity continues to exert significant influence on communication and knowledge-sharing programs (Yuan & Sun, 2020), suggesting that regional collaborations could be strengthened through structured platforms. Beyond institutional networks, fostering balanced development across disciplines is equally important. Our multidisciplinary research analysis underscores notable variations in output levels across different fields call for greater emphasis on underrepresented domains such as ecology, engineering, and chemistry, where harnessing interdisciplinary strengths could substantially enrich the overall research landscape.

The keyword trend and cluster analysis reveal that rice research in Bangladesh has evolved in response to immediate pressures rather than long-term strategy. Early work on deepwater environments and pest management shifted toward high-yielding varieties, irrigation, and market issues, and later expanded to food safety and heavy metal contamination (Catling et al., 1983; Catling et al., 1980; Mujeri, 1991; Parikh, 1988; Ravallion, 1985; Saleh et al., 1989). While these areas gained global visibility, critical domains such as mechanization, sustainable land use, and post-harvest innovations remained comparatively neglected, suggesting an imbalance in research priorities.

Recent emphasis on climate adaptation, ecofriendly production systems, and molecular genetics (Aggarwal et al., 2004; Iftekharuddaula et al., 2015; Lisa et al., 2011; Rahman et al., 2016) demonstrates progress, yet attention to social and farming-system dimensions-such as gender, integration, and nutrient management (Ara et al., 2019; Hossen et al., 2019; Nabi, 2008; Neumann et al., 2011)-has been marginal. Persistent gaps are evident: despite advances in land preparation through mechanical approach, transplanting and harvesting remain largely traditional. Furthermore, the country holds 0.4 million hectares of deepwater rice area (Nasim et al., 2018), still lacks a modern variety. Similarly, promising technologies like wet-seeding remain constrained by the absence of anaerobic genotypes. C4 rice may be a research hotspot for breaking the yield ceiling of available rice cultivars. In the global rice trade, Bangladesh has a very limited access because of non-attainment of international standard of grain parameters. Sufficient importance should be paid to address this issue. Bangladesh has been importing hybrid rice seed in spite having potential hybrid varieties. Research could be strengthened for the development of field-level hybrid rice production technology and well-organized distribution channel. Demand of ready-made and fast-food items is increasing. This industrial side is fully dependent on imported wheat grain. Remarkably, gluten-sensitivity of wheat-based food is now a concern. This entails the quest for development of rice-based fast-food and bakery items, offering a compelling direction for forthcoming research efforts.

The evolving research focus on rice research aligns with several Sustainable Development Goals (SDGs). For instance, the increasing emphasis on environmental issues, soil health, and disease management (Ali et al., 2014; Khanam et al., 2016; Paul et al., 2014) corresponds to SDG 15 (Life on Land), which seeks to protect, restore, and promote sustainable use of terrestrial ecosystems. Additionally, the exploration of eco-friendly innovations like allelopathy, biofertilizer, biopesticide, vermicompost and use of pheromone trap for insect control (Cork et al., 2005; Hoque et al., 2022; Salam & Kato-Noguchi, 2009; Singh & Singh, 1987a) resonates with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), contributing to efforts to combat climate change and promote sustainable energy solutions. Finally, the development of nutrition-enriched rice genotypes and the hybrid rice cultivars (Ibrahim et al., 2013; Swamy et al., 2019) are in line with SDG 2 (Zero Hunger), targeting to achieve food security and promote sustainability in agricultural development. These research directions hold promise for addressing critical global challenges while advancing progress towards these SDG targets.

5. Conclusion

Our study provides valuable understandings into the emerging landscape of rice research in Bangladesh. The annual progress of scientific documentation on rice research is substantial, with a consistent increase in publications over the years. It is increasingly evident that both national and international scientific communities are recognizing the vital role of Bangladesh rice in addressing global challenges. In particular, its significance is growing in the context of climate change adaptation and ensuring global food security. The leading contributors include reputed journals such as Field Crops Research, Environmental Science and Technology, Science of the Total Environment and Sustainability, along with active institutions like BRRI, BAU, BARI and several international centers as well as universities (e.g., IRRI, University of Aberdeen) that have provided major contributions to the scientific documentation. Our analysis encompassed a diverse range of crop ecosystems, comprising upland, lowland, irrigated and deepwater environments, which underscores the comprehensive nature of research in this domain. Highly cited articles on toxic elements (arsenic and cadmium) contamination and toxicity, rice-farming efficiency, climate-resilient rice, molecular breeding, and socio-economic investigation have made substantial influence on shaping the field of rice research in Bangladesh. Researchers from various disciplines, including Agriculture and Biology; Environmental Sciences; Social Sciences; Biotechnology, Genetic Engineering and Molecular Biology; multidisciplinary subject, Ecology and Engineering, have contributed to this multi-layered exploration. Keyword analysis revealed that 'Bangladesh and rice' emerged as the focal point of scientific investigation, reflecting its supremacy within this research domain. In addition, clustering of keywords into 10 distinguished research topics emphasized the multilateral nature of the research, encompassing yield performance, plant nutrition, pest management, environmental issues, economic analyses, integrated farming systems, soil fertility enhancement, sustainable resource management and food and nutrition security.

The study also highlights a fair level of cooperation among national institutions and between Bangladesh and international partners, particularly IRRI and other CGIAR centers, where such collaborations are strengthening the research landscape and facilitating technological innovations. As a look to the future, several landscapes of immediate investigations become apparent. The incorporation of mechanization into rice cultivation practices holds promise for optimizing resource utilization and enhancing overall efficiency. Exploring modern varieties for deepwater rice and anaerobic rice would satisfy the concerned dimensions. C4 rice may also be a research hotspot for breaking the yield ceiling of available rice cultivars. In the global rice trade, Bangladesh has a very limited access because of non-attainment of international standard of grain parameters, which also deserves a special attention. The current study provides an inclusive overview of the on-going research landscape, aiding the prioritization of research projects to address food security challenges judiciously. Emerging research issues include stress-tolerant rice varieties, carbon-smart farming, and grain quality improvement, with trends pointing towards climate adaptation, sustainability, and global competitiveness.

While this study offers an inclusive investigation of Bangladesh rice research, it is not without limitation. This analysis depends on data available up to a cutoff date. Therefore, the most recent developments might not be fully reflected. Moreover, the study mainly focuses on quantitative analysis and qualitative features of research. In-depth scientific inquiry and real applications of research findings are not critically addressed. The study is based on existing publications; and potential ongoing or unpublished research may not be accounted for in the analysis. The study solely considered SCOPUS database, which, while reputable, may not cover all relevant documents in the field. Forthcoming investigations could improve the research findings by adding more databases like WOSCC.

Reference

Abedin, M. J., Cotter-Howells, J., & Meharg, A. A. (2002). Arsenic uptake and accumulation in rice (*Oryza sativa* L.) irrigated with contaminated water. Plant and Soil, 240(2), 311-319. https://doi.org/10.1023/ A:1015792723288

Abedin, M. J., Cresser, M. S., Meharg, A. A., Feldmann, J., & Cotter-Howells, J. (2002). Arsenic Accumulation and Metabolism in Rice (*Oryza sativa* L.). Environmental Science & Technology, 36(5), 962-968. https://doi.org/10.1021/es0101678

Abedin, M. R., & Das, H. S. (2014). Electricity from rice husk: A potential way to electrify rural Bangladesh. International Journal of Renewable Energy Research, 4(3), 604-609. https://www.ijrer.org/ijrer/index.php/ijrer/article/view/1356/pdf

Acharjee, T. K., Halsema, G. V., Ludwig, F., & Hellegers, P. (2017). Declining trends of water requirements of dry season Boro rice in the North-West Bangladesh. Agricultural Water Management, 180(Part A), 148-159. https://doi.org/10.1016/j.agwat.2016.11.014

Acharjee, T. K., Ludwig, F., Van Halsema, G., Hellegers, P., & Supit, I. (2017). Future changes in water requirements of Boro rice in the face of climate change in North-West Bangladesh. Agricultural Water Management, 194, 172-183. https://doi.org/10.1016/j.agwat.2017.09.008

Adhikari, C., Bronson, K. F., Panuallah, G. M., Regmi, A. P., Saha, P. K., Dobermann, A., Olk, D. C., Hobbs, P. R., & Pasuquin, E. (1999). On-farm soil N supply and N nutrition in the rice–wheat system of Nepal and Bangladesh. Field Crops Research, 64(3), 273-286. https://doi.org/10.1016/S0378-4290(99)00063-5

Afrin, N., Bhuiya, S. U., Uddin, M. R., Bir, M. S. H., & Park, K. W. (2015). Combined effect of herbicides on the weed management of rice. Research on Crops, 16(3), 416-421. https://doi.org/10.5958/2348-7542.2015.00057.1

Aggarwal, P. K., Joshi, P. K., Ingram, J. S. I., & Gupta, R. K. (2004). Adapting food systems of the Indo-Gangetic plains to global environmental change: Key information needs to improve policy formulation. Environmental Science & Policy, 7(6), 487-498. https://doi.org/10.1016/j.envsci.2004.07.006

Ahiduzzaman, M., & Islam, A. K. M. S. (2016). Assessment of rice husk briquette fuel use as an alternative source of woodfuel. International Journal of Renewable Energy Research, 6(4), 1601-1611. https://www.researchgate.net/publication/312085633

Ahmed, M., Rahaman, K., Kok, A., & Hassan, Q. (2017). Remote sensing-based quantification of the

impact of flash flooding on the rice production: A case study over Northeastern Bangladesh. Sensors, 17(10), 2347.
https://doi.org/10.3390/s17102347

Ahmed, M. S. U., Khalequzzaman, M., Bashar, M. K., & Shamsuddin, A. K. M. (2016). Agro-morphological, physico-chemical and molecular characterization of rice germplasm with similar names of Bangladesh. Rice Science, 23(4), 211-218.
https://doi.org/10.1016/j.rsci.2016.06.004

Ahmed, N., & Garnett, S. T. (2011). Integrated rice-fish farming in Bangladesh: meeting the challenges of food security. Food Security, 3(1), 81-92.
https://doi.org/10.1007/s12571-011-0113-8

Ahmed, N. U., & Zeitlin, M. F. (1994). Bhat-dhara-catching rice: A folk milestone in the development of Bangladeshi children: An investigation of parental beliefs and decision making in introducing young children to family meals. Ecology of Food and Nutrition, 32(3-4), 227-238.
https://doi.org/10.1080/03670244.1994.9991403

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. (2020). Interactive effect of weeding regimes, rice cultivars, and seeding rates influence the rice-weed competition under dry direct-seeded condition. Sustainability, 13(1), 317.
https://doi.org/10.3390/su13010317

Akbar, M. A., Islam, M. N., Bhuiya, M. S. U., Islam, M. R., Hossain, M. A., & Stone, G. M. (2000). Integration of fodder legumes into rice-based cropping systems in Bangladesh: Production of Lathyrus sativus and its use as a supplement to straw-based rations of dairy cows. Asian-Australasian Journal of Animal Sciences, 13, 526-528.
https://api.semanticscholar.org/CorpusID:55546057

Al-Forkan, M., Rahim, M. A., Chowdhury, T., Akter, P., & Khaleda, L. (2005). Development of highly in vitro callogenesis and regeneration system for some salt tolerant rice (*Oryza sativa* L.) cultivars of Bangladesh. Biotechnology (Faisalabad), 4(3), 230-234.
https://doi.org/10.3923/biotech.2005.230.234

Al Rmalli, S. W., Haris, P. I., Harrington, C. F., & Ayub, M. (2005). A survey of arsenic in foodstuffs on sale in the United Kingdom and imported from Bangladesh. Science of The Total Environment, 337(1-3), 23-30.
https://doi.org/10.1016/j.scitotenv.2004.06.008

Alam, M. J., Al-Mahmud, A., Islam, M. A., Hossain, M. F., Ali, M. A., Dessoky, E. S., El-Hallous, E. I., Hassan, M. M., Begum, N., & Hossain, A. (2021). Crop diversification in rice-based cropping systems improves the system productivity, profitability and sustainability. Sustainability, 13(11), 6288.
https://doi.org/10.3390/su13116288

Alam, M. J., Begum, I. A., Rahman, S., Buysse, J., & Van Huylenbroeck, G. (2014). Tracing the impact of market reform on productivity growth of rice at the farm level in Bangladesh. Journal of the Asia Pacific Economy, 19(3), 391-408.
https://doi.org/10.1080/13547860.2014.908533

Alam, M. Z. (1975). Entomological Problems of Agriculture in Bangladesh. Pest Articles & News Summaries, 21(4), 380-383.
https://doi.org/10.1080/09670877509411429

Ali, M. A., Sattar, M. A., Islam, M. N., & Inubushi, K. (2014). Integrated effects of organic, inorganic and biological amendments on methane emission, soil quality and rice productivity in irrigated paddy ecosystem of Bangladesh: Field study of two consecutive rice growing seasons. Plant and Soil, 378(1-2), 239-252.
https://doi.org/10.1007/s11104-014-2023-y

Ara, G., Khanam, M., Rahman, A. S., Islam, Z., Farhad, S., Sanin, K. I., Khan, S. S., Rahman, M. M., Majoor, H., & Ahmed, T. (2019). Effectiveness of micronutrient-fortified rice consumption on anaemia and zinc status among vulnerable women in Bangladesh. PLOS ONE, 14(1), e0210501.
https://doi.org/10.1371/journal.pone.0210501

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics, 11(4), 959-975.
https://doi.org/10.1016/j.joi.2017.08.007

Atlas Big. (2023). World rice production by country. Retrieved Accessed 03 October 2023 from https://www.atlasbig.com/en-au/countries-by-rice-production

Azizur Rahman, M., Hasegawa, H., Mahfuzur Rahman, M., Nazrul Islam, M., Majid Miah, M. A., & Tasmen, A. (2007). Effect of arsenic on photosynthesis, growth and yield of five widely cultivated rice (*Oryza sativa* L.) varieties in Bangladesh. Chemosphere, 67(6), 1072-1079.
https://doi.org/10.1016/j.chemosphere.2006.11.061

Basunia, M. A., & Abe, T. (2001). Design and construction of a simple three-shelf solar rough rice dryer. AMA, Agricultural Mechanization in Asia, Africa and Latin America, 32(3), 54-59.
https://www.researchgate.net/publication/286867728

BBS. (2016). Household income and expenditure survey 2016. Bangladesh Bureau of Statistics. Government of Bangladesh, Dhaka.
https://drive.google.com/file/d/1TmUmC-0M3wC5IN6_tUxZUvTW2rmUxMce/view

BBS. (2020). Statistical year book of Bangladesh 2019 (39th edition ed.). Bangladesh Bureau of Statistics, Statistics & Informatics Division (SID), Ministry of Planning, Government of the People's Republic of Bangladesh.
https://bcpabd.com/wp-content/uploads/2021/04/Statistical-Yearbook-of-Bangladesh-2019.pdf

Bera, A. K., & Kelley, T. G. (1990). Adoption of high yielding rice varieties in Bangladesh. Journal of Development Economics, 33(2), 263-285.
https://doi.org/10.1016/0304-3878(90)90024-6

Biswas, P. S., Swamy, B. P. M., Kader, M. A., Hossain, M. A., Boncodin, R., Samia, M., Hassan, M. L., Wazuddin, M., MacKenzie, D., & Reinke, R. (2021). Development and field evaluation of near-isogenic lines of GR2-EBRRI dhan29 golden rice. Frontiers in Plant Science, 12, 619739. https://doi.org/10.3389/fpls.2021.619739

Brammer, H. (1987). Drought in Bangladesh: Lessons for planners and administrators. Disasters, 11(1), 21-29. https://doi.org/10.1111/j.1467-7717.1987.tb00611.x

Brolley, M. (2015, 2015). Rice security is food security for much of the world. Rice Today. International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines., 14(4), 30-32. http://books.irri.org/RT14_4_content.pdf

BRRI. (2014). About BRRI: A very short introduction. Bangladesh Rice Research Institute, Gazipur 1701, Publication 6. https://brri.portal.gov.bd/sites/default/files/files/brri.portal.gov.bd/page/19314eee_5fb5_48c3_801e_cc2f40c0d579/About_BRRI.pdf

Catling, H. D., Islam, Z., & Alam, B. (1983). Egg parasitism of the yellow rice borer, *Scirpophaga incertulas* [Lep.: Pyralidae] in Bangladesh deepwater rice. Entomophaga, 28(3), 227-239. https://doi.org/10.1007/BF02372173

Catling, H. D., Islam, Z., & Pattrasudhi, R. (1987). Assessing yield losses in deepwater rice due to yellow stem borer, *Scirpophaga incertulas* (Walker), in Bangladesh and Thailand. Crop Protection, 6(1), 20-27. https://doi.org/10.1016/0261-2194(87)90023-8

Catling, H. D., Thornhill, E. W., & Islam, Z. (1980). A boat-mounted spray boom for deepwater rice. Tropical Pest Management, 26(1), 56-60. https://doi.org/10.1080/09670878009414285

Chen, C.-C., McCarl, B., & Chang, C.-C. (2012). Climate change, sea level rise and rice: global market implications. Climatic Change, 110(3-4), 543-560. https://doi.org/10.1007/s10584-011-0074-0

Chen, C., Dubin, R., & Kim, M. C. (2014). Emerging trends and new developments in regenerative medicine: A scientometric update (2000 - 2014). Expert Opinion on Biological Therapy, 14(9), 1295-1317. https://doi.org/10.1517/14712598.2014.920813

Chen, D., Liu, Z., Luo, Z., Webber, M., & Chen, J. (2016). Bibliometric and visualized analysis of emergy research. Ecological Engineering, 90, 285-293. https://doi.org/10.1016/j.ecoleng.2016.01.026

Chowdhury, M. T. I., Mian, M. S., Mia, M. A. T., Rafii, M. Y., & Latif, M. A. (2015). Agro-ecological variations of sheath rot disease of rice caused by Sarocladium oryzae and DNA fingerprinting of the pathogen's population structure. Genetics and Molecular Research, 14(4), 18140-18152. https://doi.org/10.4238/2015.December.23.1

Chowdhury, R., Crost, B., & Hoffmann, V. (2022). Marketing fortified rice: Effects of aspirational messaging and association with free distribution. Food Policy, 112, 102346. https://doi.org/10.1016/j.foodpol.2022.102346

Coelli, T., Rahman, S., & Thirtle, C. (2002). Technical, allocative, cost and scale efficiencies in Bangladesh rice cultivation: A non-parametric approach. Journal of Agricultural Economics, 53(3), 607-626. https://doi.org/10.1111/j.1477-9552.2002.tb00040.x

Cork, A., Iles, M. J., Kamal, N. Q., Choudhury, J. C. S., Rahman, M. M., & Islam, M. (2005). An old pest, a new solution: Commercializing rice stem borer pheromones in Bangladesh. Outlook on Agriculture, 34(3), 181-187. https://doi.org/10.5367/000000005774378793

Das, H. K., Mitra, A. K., Sengupta, P. K., Hossain, A., Islam, F., & Rabbani, G. H. (2004). Arsenic concentrations in rice, vegetables, and fish in Bangladesh: A preliminary study. Environment International, 30(3), 383-387. https://doi.org/10.1016/j.envint.2003.09.005

Datta, D., & Surajit, K. (1981). The climatic environment and its effects on rice production. Pages 9-40 in Principles and practices of rice production. John Wiley and Sons, New York. http://books.irri.org/0471097608_content.pdf

Datta, J., Wei, Q., Yang, Q., Wan, P.-J., He, J.-C., Wang, W.-X., Lai, F.-X., Ali, M. P., & Fu, Q. (2021). Current resistance status of the brown planthopper Nilaparvata lugens (Stål) to commonly used insecticides in China and Bangladesh. Crop Protection, 150, 105789. https://doi.org/10.1016/j.cropro.2021.105789

Dean, G. J. (1979). The major insect pests of rice, sugarcane and jute in Bangladesh. Pest Articles & News Summaries, 25(4), 378-385. https://doi.org/10.1080/09670877909414358

Duxbury, J. M., Mayer, A. B., Lauren, J. G., & Hassan, N. (2003). Food chain aspects of arsenic contamination in Bangladesh: Effects on quality and productivity of rice. Journal of Environmental Science and Health, Part A, 38(1), 61-69. https://doi.org/10.1081/ESE-120016881

Edmondson, A. C., & Harvey, J.-F. (2018). Cross-boundary teaming for innovation: Integrating research on teams and knowledge in organizations. Human Resource Management Review, 28(4), 347-360. https://doi.org/10.1016/j.hrmr.2017.03.002

FPMU. (2020). Bangladesh food situation report, April-June 2020. Food planning and monitoring unit, Ministry of Food, Government People's Republic of Bangladesh, Dhaka, Bangladesh. Retrieved Accessed 03 October 2023 from http://fpmu.gov.bd/agridrupal/sites/default/files/FSR_121.pdf

Frei, M., Razzak, M. A., Hossain, M. M., Oehme, M., Dewan, S., & Becker, K. (2007). Performance of common carp, *Cyprinus carpio* L. and Nile tilapia, Oreochromis niloticus (L.) in integrated rice-fish

culture in Bangladesh. Aquaculture, 262(2-4), 250-259.
https://doi.org/10.1016/j.aquaculture.2006.11.019

Fulda, B., Voegelin, A., & Kretzschmar, R. (2013). Redox-controlled changes in cadmium solubility and solid-phase speciation in a paddy soil as affected by reducible sulfate and copper. Environmental Science & Technology, 47(22), 12775-12783.
https://doi.org/10.1021/es401997d

Gaihre, Y. K., Singh, U., Islam, S. M. M., Huda, A., Islam, M. R., Satter, M. A., Sanabria, J., Islam, M. R., & Shah, A. L. (2015). Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. Geoderma, 259-260, 370-379.
https://doi.org/10.1016/j.geoderma.2015.06.001

Gathala, M. K., Timsina, J., Islam, M. S., Rahman, M. M., Hossain, M. I., Harun-Ar-Rashid, M., Ghosh, A. K., Krupnik, T. J., Tiwari, T. P., & McDonald, A. (2015). Conservation agriculture based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice-maize systems: Evidence from Bangladesh. Field Crops Research, 172, 85-98.
https://doi.org/10.1016/j.fcr.2014.12.003

Glaszmann, J. C. (1987). Isozymes and classification of Asian rice varieties. Theoretical and Applied Genetics, 74(1), 21-30.
https://doi.org/10.1007/BF00290078

Greeley, M. (1982). Farm-level Post-harvest food losses: The myth of the soft third option. The IDS Bulletin, 13(3), 51-60.
https://doi.org/10.1111/j.1759-5436.1982.mp13003007.x

Guerrero-Bote, V. P., Chinchilla-Rodríguez, Z., Mendoza, A., & De Moya-Anegón, F. (2021). Comparative Analysis of the Bibliographic Data Sources Dimensions and Scopus: An Approach at the Country and Institutional Levels. Frontiers in Research Metrics and Analytics, 5, 593494.
https://doi.org/10.3389/frma.2020.593494

Halder, D., Bhowmick, S., Biswas, A., Chatterjee, D., Nriagu, J., Guha Mazumder, D. N., Šlejkovec, Z., Jacks, G., & Bhattacharya, P. (2013). Risk of arsenic exposure from drinking water and dietary components: Implications for risk management in rural Bengal. Environmental Science & Technology, 47(2), 1120-1127.
https://doi.org/10.1021/es303522s

Haque, M. E., Bell, R. W., Islam, M. A., & Rahman, M. A. (2016). Minimum tillage unpuddled transplanting: An alternative crop establishment strategy for rice in conservation agriculture cropping systems. Field Crops Research, 185, 31-39.
https://doi.org/10.1016/j.fcr.2015.10.018

Haque, M. I., & Chowdhury, S. D. (1994). Use of rice husk litter at different depths for broiler chicks during summer. British Poultry Science, 35(5), 809-812.
https://doi.org/10.1080/00071669408417745

Haque, M. M., Biswas, J. C., Akter, M., Maniruzaman, M., & Kabir, M. S. (2019). Carbon budget and aggregate stability of paddy soil under continuous organic amendment. Communications in Soil Science and Plant Analysis, 50(15), 1829-1837.
https://doi.org/10.1080/00103624.2019.1635148

Haque, M. M., Datta, J., Ahmed, T., Ehsanullah, M., Karim, M. N., Akter, M. S., Iqbal, M. A., Baazeem, A., Hadifa, A., Ahmed, S., & El Sabagh, A. (2021). Organic amendments boost soil fertility and rice productivity and reduce methane emissions from paddy fields under sub-tropical conditions. Sustainability, 13(6), 3103.
https://doi.org/10.3390/su13063103

Haque, M. M., Little, D. C., Barman, B. K., & Wahab, M. A. (2010). The adoption process of rice field-based fish seed production in Northwest Bangladesh: An understanding through quantitative and qualitative investigation. The Journal of Agricultural Education and Extension, 16(2), 161-177.
https://doi.org/10.1080/13892241003651415

Haque, M. M., Saleque, M. A., Shah, A. L., Biswas, J. C., & Kim, P. J. (2015). Long-Term effects of Sulfur and Zinc fertilization on rice productivity and nutrient efficiency in double rice cropping paddy in Bangladesh. Communications in Soil Science and Plant Analysis, 46(22), 2877-2887.
https://doi.org/10.1080/00103624.2015.1104333

Haroon, A. K. Y., & Pittman, K. A. (1997). Rice-fish culture: Feeding, growth and yield of two size classes of Puntius gonionotus Bleeker and Oreochromis spp. in Bangladesh. Aquaculture, 154(3-4), 261-281.
https://doi.org/10.1016/S0044-8486(97)00061-6

Harvey, C. F., Ashfaque, K. N., Yu, W., Badruzzaman, A. B. M., Ali, M. A., Oates, P. M., Michael, H. A., Neumann, R. B., Beckie, R., Islam, S., & Ahmed, M. F. (2006). Groundwater dynamics and arsenic contamination in Bangladesh. Chemical Geology, 228(1-3), 112-136.
https://doi.org/10.1016/j.chemgeo.2005.11.025

Hashem E, A. R., Md Salleh, N. Z., Abdullah, M., Ali, A., Faisal, F., & Nor, R. M. (2023). Research trends, developments, and future perspectives in brand attitude: A bibliometric analysis utilizing the Scopus database (1944–2021). Heliyon, 9(1), e12765.
https://doi.org/10.1016/j.heliyon.2022.e12765

Hoque, T. S., Hasan, A. K., Hasan, M. A., Nahar, N., Dey, D. K., Mia, S., Solaiman, Z. M., & Kader, M. A. (2022). Nutrient release from vermicompost under anaerobic conditions in two contrasting soils of Bangladesh and its effect on wetland rice crop. Agriculture, 12(3), 376.
https://doi.org/10.3390/agriculture12030376

Hossain, K., Timsina, J., Johnson, D. E., Gathala, M. K., & Krupnik, T. J. (2020). Multi-year weed community dynamics and rice yields as influenced by tillage, crop establishment, and weed control: Implications for rice-maize rotations in the eastern Gangetic plains. Crop Protection, 138, 105334. https://doi.org/10.1016/j.cropro.2020.105334

Hossain, M., Bose, M. L., & Mustafi, B. A. A. (2006). Adoption and productivity impact of modern rice varieties in Bangladesh. The Developing Economies, 44(2), 149-166. https://doi.org/10.1111/j.1746-1049.2006.00011.x

Hossain, M. F., Elahi, S. F., White, S. K., Alam, Q. K., Rother, J. A., & Gaunt, J. L. (2012). Nitrogen budgets for Boro rice (*Oryza sativa* L.) fields in Bangladesh. Field Crops Research, 131, 97-109. https://doi.org/10.1016/j.fcr.2012.02.029

Hossain, M. F., White, S. K., Elahi, S. F., Sultana, N., Choudhury, M. H. K., Alam, Q. K., Rother, J. A., & Gaunt, J. L. (2005). The efficiency of nitrogen fertiliser for rice in Bangladeshi farmers' fields. Field Crops Research, 93(1), 94-107. https://doi.org/10.1016/j.fcr.2004.09.017

Hossain, M. S., Hossain, A., Sarkar, M. A. R., Jahiruddin, M., Teixeira Da Silva, J. A., & Hossain, M. I. (2016). Productivity and soil fertility of the rice-wheat system in the High Ganges River Floodplain of Bangladesh is influenced by the inclusion of legumes and manure. Agriculture, Ecosystems & Environment, 218, 40-52. https://doi.org/10.1016/j.agee.2015.11.017

Hossen, M. A., Hossain, M. M., Haque, M. E., & Bell, R. W. (2018). Transplanting into non-puddled soils with a small-scale mechanical transplanter reduced fuel, labour and irrigation water requirements for rice (*Oryza sativa* L.) establishment and increased yield. Field Crops Research, 225, 141-151. https://doi.org/10.1016/j.fcr.2018.06.009

Hossen, M. A., Huda, M., Islam, M. S., Bhuiyan, M., Rahman, M., & Nath, B. (2013). Design and development of a manually operated urea supper granule (USG) applicator. Ama, Agricultural Mechanization in Asia, Africa & Latin America, 44, 85-91. https://www.researchgate.net/publication/290102864

Hossen, M. A., Kamruzzaman, M., Rahman, M., & Kabir, M. (2019). Fertilizers application simultaneously with mechanical rice transplanting in Bangladesh. Agricultural Engineering International : The CIGR e-journal, 21(4), 64-74. https://www.researchgate.net/publication/341985319

Hotz, C., Kabir, K. A., Dipti, S. S., Arsenault, J. E., & Bipul, M. (2015). Rice fortification with zinc during parboiling may improve the adequacy of zinc intakes in Bangladesh. Journal of the Science of Food and Agriculture, 95(2), 379-385. https://doi.org/10.1002/jsfa.6730

Howlader, A. J., & Matin, A. S. M. A. (1988). Observations on the pre-harvest infestation of paddy by stored grain pests in Bangladesh. Journal of Stored Products Research, 24(4), 229-231. https://doi.org/10.1016/0022-474X(88)90024-0

Hsiao, R.-L., Tsai, D.-H., & Lee, C.-F. (2012). Collaborative knowing: The adaptive nature of cross-boundary spanning. Journal of Management Studies, 49(3), 463-491. https://doi.org/10.1111/j.1467-6486.2011.01024.x

Ibrahim, M., Peng, S. B., Tang, Q. Y., Huang, M., Jiang, P., & Zou, Y. B. (2013). Comparisons of yield and growth behaviors of hybrid rice under different nitrogen management methods in tropical and subtropical environments. Journal of Integrative Agriculture, 12(4), 621-629. https://doi.org/10.1016/S2095-3119(13)60280-4

Iftekharuddaula, K. M., Ahmed, H. U., Ghosal, S., Moni, Z. R., Amin, A., & Ali, M. S. (2015). Development of new submergence tolerant rice variety for Bangladesh using marker-assisted backcrossing. Rice Science, 22(1), 16-26. https://doi.org/10.1016/j.rsci.2015.05.003

Iftekharuddaula, K. M., Ghosal, S., Gonzaga, Z. J., Amin, A., Barman, H. N., Yasmeen, R., Haque, M. M., Carandang, J., Collard, B. C. Y., & Septiningsih, E. M. (2016). Allelic diversity of newly characterized submergence-tolerant rice (*Oryza sativa* L.) germplasm from Bangladesh. Genetic Resources and Crop Evolution, 63(5), 859-867. https://doi.org/10.1007/s10722-015-0289-4

Islam, A. R. M. T., Shen, S. H., & Yang, S. B. (2018). Predicting design water requirement of winter paddy under climate change condition using frequency analysis in Bangladesh. Agricultural Water Management, 195, 58-70. https://doi.org/10.1016/j.agwat.2017.10.003

Islam, J., Bhuiyan, L. R., & Ghani, A. (1991). Supplemental irrigation - A safeguard technique for successful cultivation of Monsoon rice (Transplanted Aman) in Bangladesh. Irrigation and Drainage Systems, 5(4), 351-362. https://doi.org/10.1007/BF01102832

Islam, M. A., Mahalanabis, D., & Majid, N. (1994). Use of rice-based oral rehydration solution in a large diarrhoea treatment centre in Bangladesh: in-house production, use and relative cost. The Journal of Tropical Medicine and Hygiene, 97(6), 341-346. https://api.semanticscholar.org/CorpusID:35107880

Islam, M. J., & Molla, H. R. (2001). Economic weeding method for irrigated rice production in Bangladesh. Agricultural Water Management, 46(3), 267-276. https://doi.org/10.1016/S0378-3774(00)00093-7

Islam, M. M., Hoque, M. E., Rabbi, S. M. H. A., & Ali, M. S. (2011). DNA fingerprinting and diversity analysis of BRRI hybrid varieties and their corresponding parents. Plant Tissue Culture and Biotechnology, 21(2), 189-198. https://doi.org/10.3329/ptcb.v21i2.10242

Islam, M. R., Sarker, M. R. A., Sharma, N., Rahman, M. A., Collard, B. C. Y., Gregorio, G. B., & Ismail, A. M. (2016). Assessment of adaptability of recently released salt tolerant rice varieties in coastal regions of South Bangladesh. Field Crops Research, 190, 34-43.

https://doi.org/10.1016/j.fcr.2015.09.012

Islam, M. S., Quasem, M. A., & Baqui, M. A. (2004). Present status and future strategy on farm mechanization and postharvest technologies for rice production and processing in Bangladesh. AMA, Agricultural Mechanization in Asia, Africa and Latin America, 35, 59-66. https://www.researchgate.net/publication/279617651

Islam, M. S., Sarkar, M. A. R., Alam, M. J., Kashem, M. A., Rafii, M. Y., & Latif, M. A. (2014). Effect of date of transplanting on yield and yield attributing characters of aromatic fine rice in rainfed condition. Research on Crops, 15(2), 305. https://doi.org/10.5958/2348-7542.2014.00115.6

Islam, M. Z., Khalequzzaman, M., Prince, M. F. R. K., Siddique, M. A., Rashid, E. S. M. H., Ahmed, M. S. U., Pittendrigh, B. R., & Ali, M. P. (2018). Diversity and population structure of red rice germplasm in Bangladesh. PLOS ONE, 13(5), e0196096. https://doi.org/10.1371/journal.pone.0196096

Jensen, J. R., Mannan, S. M. A., & Uddin, S. M. N. (1993). Irrigation requirement of transplanted monsoon rice in Bangladesh. Agricultural Water Management, 23(3), 199-212. https://doi.org/10.1016/0378-3774(93)90028-9

Jiang, L., Wu, S., Liu, Y., & Yang, C. (2021). Grain security assessment in Bangladesh based on supply-demand balance analysis. PLOS ONE, 16(5), e0252187. https://doi.org/10.1371/journal.pone.0252187

Kabir, J., Cramb, R., Alauddin, M., Gaydon, D. S., & Roth, C. H. (2020). Farmers' perceptions and management of risk in rice/shrimp farming systems in South-West Coastal Bangladesh. Land Use Policy, 95, 104577. https://doi.org/10.1016/j.landusepol.2020.104577

Kabir, M. J., Alauddin, M., & Crimp, S. (2017). Farm-level adaptation to climate change in Western Bangladesh: An analysis of adaptation dynamics, profitability and risks. Land Use Policy, 64, 212-224. https://doi.org/10.1016/j.landusepol.2017.02.026

Kabir, M. S., Salam, M., Chowdhury, A., Rahman, N. M. F., Iftekharuddaula, K. M., Rahman, M. S., Rashid, M. H., Dipti, S. S., Islam, A., Latif, M., Islam, A. K. M. S., Hossain, M. M., Nessa, B., Ansari, T. H., Ali, M. A., & Biswas, J. K. (2016). Rice vision for Bangladesh: 2050 and beyond. Bangladesh Rice Journal, 19(2), 1-18. https://doi.org/10.3329/brj.v19i2.28160

Kabir, M. S., Salam, M., Islam, A., Sarkar, M. A. R., Mamun, M., Rahman, M., Nessa, B., Kabir, M., Shozib, H., Hossain, M., Chowdhury, A., Nasim, M., Iftekharuddaula, K., Hossain, M., Bhuiyan, M., Karmakar, B., Rahman, M., Haque, M., Khatun, M., . . . Rahman, N. (2021). Doubling rice productivity in Bangladesh: A way to achieving SDG 2 and moving forward. Bangladesh Rice Journal, 24(2), 1-47. https://doi.org/10.3329/brj.v24i2.53447

Kezar, A. (2006). Redesigning for collaboration in learning initiatives: An examination of four highly collaborative campuses. The Journal of Higher Education, 77(5), 804-838. https://www.jstor.org/stable/3838788

Khan, M. A., Islam, M. R., Panaullah, G. M., Duxbury, J. M., Jahiruddin, M., & Loeppert, R. H. (2009). Fate of irrigation-water arsenic in rice soils of Bangladesh. Plant and Soil, 322(1-2), 263-277. https://doi.org/10.1007/s11104-009-9914-3

Khan, M. A. I., Latif, M. A., Khalequzzaman, M., Tomita, A., Ali, M. A., & Fukuta, Y. (2017). Genetic variation in resistance to blast (*Pyricularia oryzae* Cavara) in rice (*Oryza sativa* L.) germplasms of Bangladesh. Breeding Science, 67(5), 493-499. https://doi.org/10.1270/jsbbs.17039

Khanam, S., Akanda, A. M., Ali, M. A., Kyndt, T., & Gheysen, G. (2016). Identification of Bangladeshi rice varieties resistant to ufra disease caused by the nematode Ditylenchus angustus. Crop Protection, 79, 162-169. https://doi.org/10.1016/j.cropro.2015.09.009

Khush, G. S. (1984). Terminology for rice growing environments. IRRI. https://pdf.usaid.gov/pdf_docs/PNAAR582.pdf

Ladha, J. K., Rao, A. N., Raman, A. K., Padre, A. T., Dobermann, A., Gathala, M., Kumar, V., Saharawat, Y., Sharma, S., Piepho, H. P., Alam, M. M., Liak, R., Rajendran, R., Reddy, C. K., Parsad, R., Sharma, P. C., Singh, S. S., Saha, A., & Noor, S. (2016). Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. Global Change Biology, 22(3), 1054-1074. https://doi.org/10.1111/gcb.13143

LaFranchi, W. (2015, 2015). From famine to food basket: how Bangladesh became a model for reducing hunger. The Christian Science Monitor – CSMonitor.com. http://www.csmonitor.com/USA/ForeignPolicy/2015/0617

Latif, M. A., Islam, M. R., Ali, M. Y., & Saleque, M. A. (2005). Validation of the system of rice intensification (SRI) in Bangladesh. Field Crops Research, 93(2-3), 281-292. https://doi.org/10.1016/j.fcr.2004.10.005

Lisa, L. A., Elias, S. M., Rahman, M. S., Shahid, S., Iwasaki, T., Hasan, A. K. M. M., Kosuge, K., Fukami, Y., & Seraj, Z. I. (2011). Physiology and gene expression of the rice landrace Horkuch under salt stress. Functional Plant Biology, 38(4), 282. https://doi.org/10.1071/FP10198

Lv, W., Zhao, X., Wu, P., Lv, J., & He, H. (2021). A scientometric analysis of worldwide intercropping research based on web of science database between 1992 and 2020. Sustainability, 13(5), 2430. https://doi.org/10.3390/su13052430

Magadán-Díaz, M., & Rivas-García, J. I. (2022). Publishing industry: A bibliometric analysis of the scientific production indexed in scopus. Publishing

Research Quarterly, 38(4), 665-683. https://doi.org/10.1007/s12109-022-09911-3

Maniruzzaman, M., Talukder, M. S. U., Khan, M. H., Biswas, J. C., & Nemes, A. (2015). Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. Agricultural Water Management, 159, 331-340. https://doi.org/10.1016/j.agwat.2015.06.022

Manurung, B., Hasairin, A., & Daulae, A. H. (2020). Molecular analysis of rice green leafhopper, Nephotettix virescens (Distant) from Samosir Island-Indonesia using mitochondrial COI gene. Journal of Entomological Research, 44(2), 183. https://doi.org/10.5958/0974-4576.2020.00034.1

Matthews, R. B., Kropff, M. J., Horie, T., & Bachelet, D. (1997). Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. Agricultural Systems, 54(3), 399-425. https://doi.org/10.1016/S0308-521X(95)00060-I

Mayer, A.-M. B., Latham, M. C., Duxbury, J. M., Hassan, N., & Frongillo, E. A. (2007). A food-based approach to improving zinc nutrition through increasing the zinc content of rice in Bangladesh. Journal of Hunger & Environmental Nutrition, 2(1), 19-39. https://doi.org/10.1080/19320240802077797

Meharg, A. A., Lombi, E., Williams, P. N., Scheckel, K. G., Feldmann, J., Raab, A., Zhu, Y., & Islam, R. (2008). Speciation and localization of arsenic in white and brown rice grains. Environmental Science & Technology, 42(4), 1051-1057. https://doi.org/10.1021/es702212p

Meharg, A. A., Norton, G., Deacon, C., Williams, P., Adomako, E. E., Price, A., Zhu, Y., Li, G., Zhao, F.-J., McGrath, S., Villada, A., Sommella, A., De Silva, P. M. C. S., Brammer, H., Dasgupta, T., & Islam, M. R. (2013). Variation in rice cadmium related to human exposure. Environmental Science & Technology, 47(11), 5613-5618. https://doi.org/10.1021/es400521h

Meharg, A. A., & Rahman, M. M. (2003). Arsenic contamination of Bangladesh paddy field soils: Implications for rice contribution to arsenic consumption. Environmental Science & Technology, 37(2), 229-234. https://doi.org/10.1021/es0259842

Meharg, A. A., Williams, P. N., Adomako, E., Lawgali, Y. Y., Deacon, C., Villada, A., Cambell, R. C. J., Sun, G., Zhu, Y.-G., Feldmann, J., Raab, A., Zhao, F.-J., Islam, R., Hossain, S., & Yanai, J. (2009). Geographical variation in total and inorganic arsenic content of polished (White) rice. Environmental Science & Technology, 43(5), 1612-1617. https://doi.org/10.1021/es802612a

Miah, N. M., Ahmed, A. U., & Mustafi, B. A. A. (2004). Adopting modern rice technologies in flood-prone areas: Status, constraints and opportunities. Proceedings of the international workshop on floodprone rice systems held in Gazipur, Bangladesh, 9-11 January 2001. International Rice Research Institute, P. O. Box 933, Manila, Philippines.,

Mian, M. H., & Stewart, W. D. P. (1985). A15N tracer study to compare nitrogen supply by Azolla and ammonium sulphate to IR8 rice plants grown under flooded conditions. Plant and Soil, 83(3), 371-379. https://doi.org/10.1007/BF02184449

Moomaw, J. C., & Vergara, B. S. (1964, 1964/02//). The environment of tropical rice production. Pages 3-13 in International Rice Research Institute. The mineral nutrition of the rice plant. Proceedings of a symposium at the International Rice Research Institute,

Moslehuddin, M., Zofar, A., Laizoo, S., & Egashira, K. (1999). Trace elements in Bangladesh paddy soils. Communications in Soil Science and Plant Analysis, 30(13-14), 1975-1996. https://doi.org/10.1080/00103629909370347

Mottaleb, K. A., Gumma, M. K., Mishra, A. K., & Mohanty, S. (2015). Quantifying production losses due to drought and submergence of rainfed rice at the household level using remotely sensed MODIS data. Agricultural Systems, 137, 227-235. https://doi.org/10.1016/j.agsy.2014.08.014

Mottaleb, K. A., & Mishra, A. K. (2016). Rice consumption and grain-type preference by household: A Bangladesh case. Journal of Agricultural and Applied Economics, 48(3), 298-319. https://doi.org/10.1017/ aae.2016.18

Mujeri, M. K. (1991). The impact of the HYV technology on the variability of rice production and yield: Some evidence from Bangladesh. The Pakistan Development Review, 30(1), 63-81. https://doi.org/10.30541/v30i1pp.63-81

Mustow, S. E. (2002). The effects of shading on phytoplankton photosynthesis in rice-fish fields in Bangladesh. Agriculture, Ecosystems & Environment, 90(1), 89-96. https://doi.org/10.1016/S0167-8809(01)00171-2

Nabi, R. (2008). Constraints to the adoption of rice-fish farming by smallholders in Bangladesh: A farming systems analysis. Aquaculture Economics & Management, 12(2), 145-153. https://doi.org/10.1080/13657300802110844

Nasim, M., Shahidullah, S., Saha, A., Muttaleb, M., Aditya, T., Ali, M., & Kabir, M. (2018). Distribution of crops and cropping patterns in Bangladesh. Bangladesh Rice Journal, 21(2), 1-55. https://doi.org/10.3329/brj.v21i2.38195

Nath, N. C. (2015, 2015). Food security in Bangladesh: Status, challenges and strategic policy options.

Neumann, R. B., St. Vincent, A. P., Roberts, L. C., Badruzzaman, A. B. M., Ali, M. A., & Harvey, C. F. (2011). Rice field geochemistry and hydrology: An explanation for why groundwater irrigated fields in Bangladesh are net sinks of arsenic from groundwater. Environmental Science & Technology, 45(6), 2072-2078.

https://doi.org/10.1021/es102635d

Palacpac, A. C. (1980). World rice statistics. IRRI. https://books.google.com.bd/books?id=9XTQMgEACAAJ

Panaullah, G. M., Alam, T., Hossain, M. B., Loeppert, R. H., Lauren, J. G., Meisner, C. A., Ahmed, Z. U., & Duxbury, J. M. (2009). Arsenic toxicity to rice (*Oryza sativa* L.) in Bangladesh. Plant and Soil, 317(1-2), 31-39. https://doi.org/ 10.1007/s11104-008-9786-y

Parikh, A. (1988). Impact of risk on HYV adoption in Bangladesh. Agricultural Economics, 2(2), 167-178. https://doi.org/10.1016/ 0169-5150(88)90015-1

Parsons, B. J., Newbury, H. J., & Jackson, M. T. (1999). The genetic structure and conservation of aus, aman and boro rices from Bangladesh. Genetic Resources and Crop Evolution, 46(6), 587-598. https://doi.org/10.1023/A:1008749532171

Parsons, B. J., Newbury, H. J., Jackson, M. T., & Ford-Lloyd, B. V. (1997). Contrasting genetic diversity relationships are revealed in rice (*Oryza sativa* L.) using different marker types. Molecular Breeding, 3(2), 115-125. https://doi.org/10.1023/A:1009635721319

Paul, J., Choudhary, A. K., Suri, V. K., Sharma, A. K., Kumar, V., & Shobhna. (2014). Bioresource nutrient recycling and its relationship with biofertility indicators of soil health and nutrient dynamics in rice-wheat cropping system. Communications in Soil Science and Plant Analysis, 45(7), 912-924. https://doi.org/10.1080/00103624.2013.867051

Polizzotto, M. L., Lineberger, E. M., Matteson, A. R., Neumann, R. B., Badruzzaman, A. B. M., & Ashraf Ali, M. (2013). Arsenic transport in irrigation water across rice-field soils in Bangladesh. Environmental Pollution, 179, 210-217. https://doi.org/10.1016/j.envpol.2013.04.025

Promthai, C., Rerkasem, B., Fukai, S., & Huang, L. (2009). Iron fortification and parboiled rice quality: Appearance, cooking quality and sensory attributes. Journal of the Science of Food and Agriculture, 89(15), 2565-2571. https://doi.org/10.1002/jsfa.3753

Rahman, M., Shahidul, M., Bir, H., Islam, M., Mohammad, M. A., Mohammad, N.-N., Nurun-Nabi, M., Nain, J., Islam, M., Islam, M., Oh, T. K., & Park, K. (2018). Impact of short duration and high yielding aman rice varieties in Manga areas of Bangladesh. Bioscience Research, 15(1), 513-517. https://www.researchgate.net/publication/351277315

Rahman, M. A., Hasegawa, H., Rahman, M. A., Rahman, M. M., & Miah, M. A. M. (2006). Influence of cooking method on arsenic retention in cooked rice related to dietary exposure. Science of The Total Environment, 370(1), 51-60. https://doi.org/10.1016/j.scitotenv.2006.05.018

Rahman, M. A., Hasegawa, H., Rahman, M. M., Rahman, M. A., & Miah, M. A. M. (2007). Accumulation of arsenic in tissues of rice plant (Oryza sativa L.) and its distribution in fractions of rice grain. Chemosphere, 69(6), 942-948. https://doi.org/10.1016/j.chemosphere.2007.05.044

Rahman, M. A., Rahman, M. M., Reichman, S. M., Lim, R. P., & Naidu, R. (2014). Heavy metals in Australian grown and imported rice and vegetables on sale in Australia: Health hazard. Ecotoxicology and Environmental Safety, 100, 53-60. https://doi.org/10.1016/j.ecoenv.2013.11.024

Rahman, M. A., Thomson, M. J., Shah-E-Alam, M., De Ocampo, M., Egdane, J., & Ismail, A. M. (2016). Exploring novel genetic sources of salinity tolerance in rice through molecular and physiological characterization. Annals of Botany, 117(6), 1083-1097. https:// doi.org/10.1093/aob/mcw030

Rahman, M. S., Das, K. C., Das, D. K., Biswas, K., Chowdhury, M. B. H., Karim, N. H., Salam, M. A., & Seraj, Z. I. (1970). Breeding and anther derived lines of rice (*Oryza sativa* L.) for saline coastal areas of Bangladesh. Bangladesh Journal of Botany, 39(1), 71-78. https://doi.org/10.3329/bjb.v39i1.5529

Rahman, N. M. F., Malik, W. A., Kabir, M. S., Baten, M. A., Hossain, M. I., Paul, D. N. R., Ahmed, R., Biswas, P. S., Rahman, M. C., Rahman, M. S., Iftekharuddaula, K. M., Hadasch, S., Schmidt, P., Islam, M. R., Rahman, M. A., Atlin, G. N., & Piepho, H. P. (2023). 50 years of rice breeding in Bangladesh: genetic yield trends. Theoretical and Applied Genetics, 136(1), 18. https://doi.org/10.1007/s00122-023-04260-x

Rahman, S. (2003). Profit efficiency among Bangladeshi rice farmers. Food Policy, 28(5-6), 487-503. https://doi.org/10.1016/j.foodpol.2003.10.001

Rahman, S. (2009). Whether crop diversification is a desired strategy for agricultural growth in Bangladesh? Food Policy, 34(4), 340-349. https://doi.org/10.1016/j.foodpol.2009.02.004

Rahman, S. (2015). Agroecological, climatic, land elevation and socio-economic determinants of pesticide use at the farm level in Bangladesh. Agriculture, Ecosystems & Environment, 212, 187-197. https://doi.org/10.1016/j.agee.2015.07.002

Rahman, S., & Rahman, M. (2009). Impact of land fragmentation and resource ownership on productivity and efficiency: The case of rice producers in Bangladesh. Land Use Policy, 26(1), 95-103. https://doi.org/10.1016/j.landusepol.2008.01.003

Rashid, M. A., Ando, K., Tanaka, K., & Kaida, Y. (1997). Village-level studies on rice-based cropping systems in the low-lying areas of Bangladesh. II. Toposequence, hydrology, land classification and cropping patterns in the Bogra District of the

Barind Tract. Japanese Journal of Crop Science, 66(1), 118-128. https://doi.org/10.1626/jcs.66.118

Rashid, M. H., Alam, M. M., Rao, A. N., & Ladha, J. K. (2012). Comparative efficacy of pretilachlor and hand weeding in managing weeds and improving the productivity and net income of wet-seeded rice in Bangladesh. Field Crops Research, 128, 17-26. https://doi.org/10.1016/j.fcr.2011.11.024

Rashid, M. H., Goswami, P. C., Hossain, M. F., Mahalder, D., Rony, M. K. I., Shirazy, B. J., & Russell, T. D. (2018). Mechanised non-puddled transplanting of boro rice following mustard conserves resources and enhances productivity. Field Crops Research, 225, 83-91. https://doi.org/10.1016/j.fcr.2018.06.006

Ravallion, M. (1985). The information efficiency of traders' price expectations in a Bangladesh rice market. Oxford Bulletin of Economics and Statistics, 47(2), 171-184. https://doi.org/10.1111/j.1468-0084.1985.mp47002005.x

Reza, H. M., Gias, Z. T., Islam, P., Sabnam, S., Jain, P., Hossain, M. H., & Alam, M. A. (2015). HPLC-DAD system-based phenolic content analysis and In Vitro antioxidant activities of rice bran obtained from Aush dhan (*Oryza sativa*) of Bangladesh: Antioxidant activity of rice bran. Journal of Food Biochemistry, 39(4), 462-470. https://doi.org/10.1111/jfbc.12154

Roberts, L. C., Hug, S. J., Dittmar, J., Voegelin, A., Kretzschmar, R., Wehrli, B., Cirpka, O. A., Saha, G. C., Ashraf Ali, M., & Badruzzaman, A. B. M. (2010). Arsenic release from paddy soils during monsoon flooding. Nature Geoscience, 3(1), 53-59. https://doi.org/10.1038/ngeo723

Roy, R., & Chan, N. W. (2015). Determinants of sustainable irrigated and rainfed rice farming in Bangladesh. Journal of Agricultural Science and Technology, 17, 1421-1435. https://www.researchgate.net/publication/284898000

Roy, R., Chan, N. W., & Ruslan, R. (2013). Development of indicators for sustainable rice farming in Bangladesh: A case study with participative multi-stakeholder involvement. World Applied Sciences Journal, 22(5), 672-682. https://www.idosi.org/wasj/wasj22(5)13/12.pdf

Saha, P. K., Ishaque, M., Saleque, M. A., Miah, M. A. M., Panaullah, G. M., & Bhuiyan, N. I. (2007). Long-term integrated nutrient management for rice-based cropping pattern: Effect on growth, yield, nutrient uptake, nutrient balance sheet, and soil fertility. Communications in Soil Science and Plant Analysis, 38(5-6), 579-610. https://doi.org/10.1080/00103620701215718

Salam, M. A., & Kato-Noguc, H. (2010). Allelopathic potential of Methanol extract of Bangladesh rice seedlings. Asian Journal of Crop Science, 2(2), 70-77. https://doi.org/10.3923/ajcs.2010.70.77

Salam, M. A., & Kato-Noguchi, H. (2009). Screening of allelopathic potential Bangladesh rice cultivars by donor-receiver bioassay. Asian Journal of Plant Sciences, 8(1), 20-27. https://doi.org/10.3923/ajps.2009.20.27

Saleh, A. F. M., Steenhuis, T. S., & Walter, M. F. (1989). Groundwater table simulation under different rice irrigation practices. Journal of Irrigation and Drainage Engineering, 115(4), 530-544. https://doi.org/10.1061/(ASCE)0733-9437(1989)115:4(530)

Saleque, M. A., Abedin, M. J., Bhuiyan, N. I., Zaman, S. K., & Panaullah, G. M. (2004). Long-term effects of inorganic and organic fertilizer sources on yield and nutrient accumulation of lowland rice. Field Crops Research, 86(1), 53-65. https://doi.org/10.1016/S0378-4290(03)00119-9

Saleque, M. A., Abedin, M. J., Panaullah, G. M., & Bhuiyan, N. I. (1998). Yield and phosphorus efficiency of some lowland rice varieties at different levels of soil-available phosphorus. Communications in Soil Science and Plant Analysis, 29(19-20), 2905-2916. https://doi.org/10.1080/00103629809370164

Saleque, M. A., Naher, U. A., Choudhury, N. N., & Hossain, A. T. M. S. (2004). Variety-Specific Nitrogen Fertilizer Recommendation for Lowland Rice. Communications in Soil Science and Plant Analysis, 35(13-14), 1891-1903. https://doi.org/10.1081/LCSS-200026811

Saleque, M. A., Uddin, M. K., Ferdous, A. K. M., & Rashid, M. H. (2007). Use of Farmers' Empirical Knowledge to Delineate Soil Fertility-Management Zones and Improved Nutrient-Management for Lowland Rice. Communications in Soil Science and Plant Analysis, 39(1-2), 25-45. https://doi.org/10.1080/00103620701758915

Sarker, M. A. R., Alam, K., & Gow, J. (2012). Exploring the relationship between climate change and rice yield in Bangladesh: An analysis of time series data. Agricultural Systems, 112, 11-16. https://doi.org/10.1016/j.agsy.2012.06.004

Sarwar, A. K. M. G., Haque, M. S., Hossen, M. Z., & Kabir, A. K. M. A. (2022). Supplementary potassium application enriched micronutrient status of purple rice (*Oryza sativa* L.). Research on Crops, 23(4), 719-728. https://doi.org/10.31830/2348-7542.2022.ROC-871

Sau, K., & Nayak, Y. (2022). Scopus based bibliometric and scientometric analysis of occupational therapy publications from 2001 to 2020. F1000 Research, 11, 155. https://doi.org/10.12688/f1000research.108772.1

Sen, S., Chakraborty, R., & Kalita, P. (2020). Rice - not just a staple food: A comprehensive review on its phytochemicals and therapeutic potential. Trends in Food Science & Technology, 97, 265-285. https://doi.org/10.1016/j.tifs.2020.01.022

Sevillano-Jimenez, J., Carrión-Chambilla, M., Espinoza-Lecca, E., Mori-Quispe, E., Contreras-Pulache, H., & Moya-Salazar, J. (2023). A bibliometric analysis of 47-years of research on public health in Peru. Electronic Journal of General Medicine, 20(4), em488. https://doi.org/10.29333/ejgm/13103

Shahid, S. (2011). Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh. Climatic Change, 105(3-4), 433-453. https://doi.org/10.1007/s10584-010-9895-5

Shahidullah, S. M., Hanafi, M. M., Ashrafuzzaman, M., Hakim, M. A., & Karim, M. R. (2011). Plant stature of aromatic rice genotypes in the environment of Bangladesh. Journal of Environmental Biology, 32(6), 821-829. http://www.ncbi.nlm.nih.gov/pubmed/22471222

Shahidullah, S. M., Hanafi, M. M., Ashrafuzzaman, M., Razi Ismail, M., Salam, M. A., & Khair, A. (2010). Biomass accumulation and energy conversion efficiency in aromatic rice genotypes. Comptes Rendus Biologies, 333(1), 61-67. https://doi.org/10.1016/j.crvi.2009.10.002

Shahidullah, S. M., Hanafi, M. M., Ashrafuzzaman, M., Uddin, M. K., & Meon, S. (2009). Analysis of lodging parameters in aromatic rice. Archives of Agronomy and Soil Science, 55(5), 525-533. https://doi.org/10.1080/03650340902737896

Shahidullah, S. M., Salam, M. A., & Khair, A. (2008). Stability analysis for grain yield and aroma in rice under different environments. Bangladesh Rice Journal, 14(1 & 2), 33-42. https://brri.portal.gov.bd/sites/default/files/files/brri.portal.gov.bd/page/ea9c4002_59f2_4df1_b0e2_f77738a7c24f/Vol-14.pdf

Shahidullah, S. M., Shirazy, B. J., Quais, M. K., Tahjib-Ul-Arif, M., & Rhaman, M. S. (2025). Unveiling global research dynamics in aromatic rice: bibliometric insights and future directions. Discover Plants, 2(1), 261. https://doi.org/10.1007/s44372-025-00348-4

Shahidullah, S. M., Shirazy, B. J., Sarkar, M. A. R., & Quais, M. K. (2024). Four decades of research on rice intercropping: A bibliometric analysis. Journal of Agriculture and Food Research, 15, 100964. https://doi.org/10.1016/j.jafr.2024.100964

Shahjahan, M. (1974). Extent of damage of unhusked stored rice by Sitotroga cerealella Oliv. (Lepidoptera, gelechiidae) in Bangladesh. Journal of Stored Products Research, 10(1), 23-26. https://doi.org/10.1016/0022-474X(74)90026-5

Shahriar, S., Paul, A. K., & Rahman, M. M. (2022). Removal of toxic and essential nutrient elements from commercial rice brands using different washing and cooking practices: Human health risk assessment. International Journal of Environmental Research and Public Health, 19(5), 2582. https://doi.org/10.3390/ijerph19052582

Shamsi, S., Khan, A. Z. M. N. A., Shahjahan, A., & Miah, S. A. (2003). Fungal species associated with sheaths and grains of sheath rot affected rice varieties from Bangladesh. Bangladesh Journal of Botany, 32(1), 17-22. https://www.researchgate.net/publication/292451351

Shi, Z., Carey, M., Meharg, C., Williams, P. N., Signes-Pastor, A. J., Triwardhani, E. A., Pandiangan, F. I., Campbell, K., Elliott, C., Marwa, E. M., Jiujin, X., Farias, J. G., Nicoloso, F. T., De Silva, P. M. C. S., Lu, Y., Norton, G., Adomako, E., Green, A. J., Moreno-Jiménez, E., . . . Meharg, A. A. (2020). Rice grain cadmium concentrations in the global supply-chain. Exposure and Health, 12(4), 869-876. https://doi.org/10.1007/s12403-020-00349-6

Singh, A. L., & Singh, P. K. (1987a). Comparative study on azolla and blue-green algae dual culture with rice. Israel Journal of Botany, 36(2), 53-61. https://doi.org/10.1080/0021213X.1987.10677069

Singh, A. L., & Singh, P. K. (1987b). The Use of Azolla Pinnata isolates as organic nitrogen sources for lowland rice (*Oryza sativa*). Experimental Agriculture, 23(2), 159-166. https://doi.org/10.1017/S0014479700016951

Singh, U., Dar, M., Singh, S., Zaidi, N., Bari, M. A., Mackill, D., Collard, B., Singh, V. N., Singh, J. P., Reddy, J. N., & Ismail, R. K. (2013). Field performance, dissemination, impact and tracking of submergence tolerant (*Sub1*) rice varieties in South Asia. SABRAO journal of breeding and genetics, 45, 112-131. https://www.researchgate.net/publication/235906946

Suh, H. S., Sato, Y. I., & Morishima, H. (1997). Genetic characterization of weedy rice (*Oryza sativa* L.) based on morpho-physiology, isozymes and RAPD markers. Theoretical and Applied Genetics, 94(3-4), 316-321. https://doi.org/10.1007/s001220050417

Sumy, M. C., Islam, M. M., & Khan, M. K. I. (2012). Comparative study between rice husk and sand incubation techniques for hatching the improved backyard poultry eggs. Livestock Research for Rural Development, 24(1), 10-11. http://www.lrrd.org/lrrd24/1/sumy24010.htm

Swamy, B. P. M., Samia, M., Boncodin, R., Marundan, S., Rebong, D. B., Ordonio, R. L., Miranda, R. T., Rebong, A. T. O., Alibuyog, A. Y., Adeva, C. C., Reinke, R., & MacKenzie, D. J. (2019). Compositional analysis of genetically engineered GR2E "Golden Rice" in comparison to that of conventional rice. Journal of Agricultural and Food Chemistry, 67(28), 7986-7994. https://doi.org/10.1021/acs.jafc.9b01524

Torres, R. O., McNally, K. L., Cruz, C. V., Serraj, R., & Henry, A. (2013). Screening of rice genebank germplasm for yield and selection of new drought tolerance donors. Field Crops Research, 147, 12-22. https://doi.org/10.1016/j.fcr.2013.03.016

Uddin, M. T., & Dhar, A. R. (2020). Assessing the impact of water-saving technologies on Boro rice farming in Bangladesh: Economic and environmental perspective. Irrigation Science, 38(2), 199-212. https://doi.org/10.1007/s00271-019-00662-2

Ullah, M., Shamsuzzaman, S. M., Islam, M., Samsuri, W., & Uddin, M. (2017). Cadmium availability and uptake by rice from lime, Cow-dung and poultry manure amended Ca-contaminated paddy soil. Bangladesh Journal of Botany, 46, 291-296. https://www.researchgate.net/publication/343207379

Wikipedia. (2023). Land use statistics by country. Retrieved Accessed on 26 October 2023 from https://en.wikipedia.org/wiki/Land_use_statistics_by_country

Yokota, H., Tanabe, K., Sezaki, M., Yano, Y., Hamabe, K., Yabuuchi, K., Tokunaga, H., Asia Arsenic Network. Research Group for Applied Geology. National Institute of, P., & Social, M. (2002). Arsenic contamination in groundwater of Samta, Bangladesh. Water Science and Technology, 46(11-12), 375-380. http://www.ncbi.nlm.nih.gov/pubmed/12523781

Yuan, B. Z., & Sun, J. (2020). Bibliometric analysis of research on the maize based on top papers during 2009-2019. COLLNET Journal of Scientometrics and Information Management, 14(1), 75-92. https://doi.org/10.1080/09737766.2020.1787110

Zavala, Y. J., & Duxbury, J. M. (2008). Arsenic in rice: I. Estimating normal levels of total arsenic in rice grain. Environmental Science & Technology, 42(10), 3856-3860. https://doi.org/10.1021/es702747y

Zhao, F. J., Harris, E., Yan, J., Ma, J., Wu, L., Liu, W., McGrath, S. P., Zhou, J., & Zhu, Y. G. (2013). Arsenic methylation in soils and its relationship with microbial arsM abundance and diversity, and as speciation in rice. Environmental Science & Technology, 47(13), 7147-7154. https://doi.org/10.1021/es304977m

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