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Rice husk fly ash as a soil amendment for dry season rice (*Oryza sativa* L.) grown in the peat soil of Bangladesh

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Abstract

Peat soil poses significant constraints on rice cultivation due to its poor physical and chemical properties. Rice husk fly ash (RHFA) has the potential to improve peat soil fertility and enhance dry-season rice (*Oryza sativa* L.) production. This study evaluated the effects of RHFA on peat soil fertility, growth, and yield-related traits of dry-season rice varieties in Bangladesh. A field study was conducted using a randomized complete block design in the peat soil with two factors: RHFA and rice varieties. The study results showed that RHFA contained considerable amounts of nutrients, including P (0.922%), K (2.250%), S (0.276%), Ca (0.439%), Mg (0.192%), Fe (0.031%), Zn (0.052%), and Na (0.85%), with a pH of 7.32. RHFA application significantly improved peat soil properties by increasing soil pH by 1.43 units, reducing salinity by 1.78 dS/m, decreasing nitrogen loss by 0.19%, and increasing organic matter by 1.87 units. It also enhanced the availability of macro- and micronutrients, including N, P, K, S, Ca, Mg, Zn, Cu, Fe, and Mn. The RHFA application improved rice growth and yield traits across all varieties. GD, GY, PH, NPM2, PL, NFGP, and 1000-gwt increased by 0.68–1.39%, 4.51–24.39%, 0.92–4.83%, 7.77–15.05%, 3.31–5.23%, 5.91–21.48%, and 2.18–4.91%, respectively, while sterility decreased by 10–32%. Among the tested varieties, BRRI dhan108 produced the highest grain yield (9.4 t/ha) and number of filled grains per panicle (243). PCA explained 65.1% of the total variability. Overall, RHFA effectively improved peat soil fertility and increased dry-season rice productivity in Bangladesh.

Introduction

Peat soil is a distinctive soil that forms from organic matter and minerals under specific climatic and topographic conditions. The peat is mature and fibrous, varying in color from brownish-black to black. It has low shear strength (5–20 kPa), high compressibility (0.9–1.5), and moisture content exceeding 100% (Sutarno and Mohamad 2023). The global extent of peatlands is approximately 415 million hectares (ha), accounting for 3% of Earth's land area (Omar et al. 2022). In Bangladesh, peat soil covers approximately 0.22 million hectares (ha), accounting for 1.6% of the country's total area (Ali et al. 2020). In the country, peat soil is typically found in several basins located between the Ganges River and the Ganges tidal floodplains of Gopalganj, Bagerhat, and nearby areas in Khulna, Barisal, and Jessore districts. Additionally, peat soil exists in the Sylhet basin of Bangladesh, covering the districts of Kishoreganj, Netrokona, Maulavibazar, and Brahmanbaria (Huq 2021).

Peatlands form from the accumulation of organic materials, including plant detritus and decomposing vegetation, in low-elevation areas of Bangladesh, such as haors and beels. Chemical analysis shows they have a high heating value and carbon content, with low ash and sulfur contents (Ali et al. 2020). In Bangladesh, peat soils are categorized into three types: fibric, sapric, and haemic (Arabia et al. 2020). The primary disadvantages of peat soil include its low bearing capacity, constant wetness, susceptibility to deep flooding, and challenges in agricultural management (Ali et al. 2020). Under these conditions, the availability of macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and phosphorus is significantly reduced (Kalbuadi et al. 2024). Additionally, micronutrients such as iron, copper, zinc, manganese, and molybdenum are deficient (Manalu et al. 2024). Conversely, the soil’s positive ion-holding capacity increases, leading to the production of many organic acids, especially phenolic acids, which can stunt crop growth (Kanjana et al. 2024). Due to these factors, plant growth in peat soils is limited, leading to reduced crop yields. Peat soils serve various purposes globally. Dried peat soils are used locally for agriculture, forestry, energy production, power plants, brick-making, multiple industries, and as a heat source for residential buildings (Vincevica-Gaile et al. 2021). Furthermore, peat soil is essential for farmers and horticulturists seeking to enhance soil quality for improved crop and fruit production. Using peat for brickmaking and as a cooking fuel helps minimize deforestation and protect the environment (Jumien et al. 2023; Ahmada et al. 2021). Although peat soils have low availability of macronutrients and micronutrients, further research is needed to enhance soil fertility and improve crop growth, particularly in rice cultivation.

Rice (Oryza sativa L.) is a staple grain essential to the diets of billions worldwide. Asia consumes the majority of the world's rice, accounting for approximately 90% (Das 2025). Bangladesh's economy remains largely dependent on agriculture, with rice (Oryza sativa L.) being the most crucial crop (Kabir et al. 2021). Over 83% of the country's grain supply comes from rice, which covers more than three-quarters of Bangladesh's arable land (Mukul et al. 2025). According to the typical daily diet of Bangladeshis, rice provides 55% of the protein and 75% of the calories (BRRI 2023). In 2024, Bangladesh produced 21.07 million metric tons of Boro (dry-season) rice (FPMU 2024), as the dry season (November-April) provides favorable conditions for rice cultivation, benefiting various ecosystems. In this context, the Bangladesh government has focused on improving soil fertility in peat soil areas, aiming to create better conditions for rice cultivation and increase rice production, thereby ensuring food security for its people.

Rice husk (RH) is a major agricultural byproduct in rice-producing countries. This rugged, dry shell surrounds and protects the outer layer of the rice kernel and is typically discarded during milling (Kordi et al. 2024). During rice milling, approximately 0.28 kg of rice husk is produced for each kilogram of rice (Tharani et al. 2024). The USDA Foreign Agricultural Service reports that global rice production hit a record high of 535.8 million tons (milled basis) in the 2024/2025 marketing year (Childs et al. 2025). According to the US Department of Agriculture's Foreign Agricultural Service (FAS), Bangladesh produced 36.8 million tons of milled rice in 2024, making it the world's third-largest rice producer (Childs et al. 2025). In recent years, worldwide rice husk production across more than 75 countries has ranged from approximately 139.54 to 230.24 million tons (Kamruzzaman et al. 2024). The amount of rice husks closely correlates with rice production in Bangladesh, with about

7.52 million tons produced annually in this major rice-producing country (Hossain et al. 2024). Additionally, approximately 20–25% of the rice husk's mass is converted into Rice Husk Fly Ash (RHFA) when it is completely burned (Indumathi et al. 2024). The mineral components in rice husk include silica, alkalis, and trace elements, as well as organic materials such as cellulose and lignin (Nzereogu et al. 2023). Silica, which constitutes 87–97% of the ash, is a rich source of organic matter and is valuable for industrial uses due to its large surface area, high porosity, and light weight (Nzereogu et al. 2023). Okoro et al. (2022) also mention that it contains 1.48% CaO, 1.23% MgO, 1.09% MnO, 1.54% Fe_3O_3, and 1.21% Al_2O_3.

The RHFA application enhances the chemical and physical properties of soil in crop fields (Gu et al. 2024). Adding RHFA to the soil increased soil pH, exchangeable potassium (K), magnesium (Mg), accessible phosphorus (P), porosity, and plant-available water (PAW) (Gu et al. 2024). Based on these properties, RHA demonstrates excellent potential as a soil amendment. In a previous study, Nelvia (2018) investigated the effects of varying fly ash application rates on peat soil to determine the optimal treatment to enhance rice growth and yield. The researchers observed that applying fly ash at rates of 5 t ha^{-1} and 25 t ha^{-1} to peat soil resulted in higher grain yields compared to other treatments. Based on this, the present study hypothesizes that applying RHFA with inorganic fertilizers positively affects peat soils by increasing soil pH and enhancing the availability of macro- and micronutrients. Nonetheless, using large amounts of RHFA may raise soluble salt and heavy metal levels in soils, which appears to be the most significant limitation (Cecire et al. 2024; Rahaja et al. 2024; Javed et al. 2023).

However, in Bangladesh, the effects of RHFA application on peat soils and on the yields of dry-season rice varieties remain unclear. Therefore, this study was conducted to determine the effect of rice husk fly ash (RHFA) on rice growth and yield components of different rice varieties grown on peat soil.

Materials and Methods

Chemical properties of the soil: Experimental field soil was collected and analyzed for chemical properties both before and after harvest

The soil was collected from the BRRI regional station in Gopalganj, Agro-ecological Zone 14 (AEZ 14), located at 23°00'47.67" N, 89°04'21.41" E. The soil sample was collected before land preparation for the experiment and after rice harvesting using an auger at a depth of 0–20 cm from various locations within the study area (Biswash et al. 2024a). The soil was then collected in a clean bucket, and the individual soil samples were combined into a single composite sample. The soil sample was then air-dried and ground to pass through a 0.25-mm sieve. Different techniques were used to determine the chemical properties of the peat soil. The electrometric (pH meter) method was used to measure soil pH (Tagami and Uchida 2025); the Kjeldahl method was used to measure total N (Gautam et al. 2023); wet oxidation methods were employed to measure organic matter (OM) (Anand et al. 2022); the Olson method was used to determine phosphorus (P) (Khan et al. 2024); spectrophotometric techniques were used to measure calcium (Ca) and boron (B) (Akhtar et al. 2022); the DTPA (diethylene triamine penta acetic acid) method was employed to assess zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) (Amy et al. 2024); the ammonium acetate (Flame photometric) method was utilized to measure potassium (K) (Badri et al. 2024); and the ammonium acetate (Atomic Absorption Spectrophotometric) method was used to determine calcium (Ca) and magnesium (Mg) (Jérémie et al. 2020).

Preparation of rice husk fly ash (RHFA) and analysis of the chemical properties

Rice husk fly ash (RHFA) was prepared in a locally fabricated rice mill. Once formed, the RHFA turns gray. To remove large particles, the collected RHFA is sieved through a 75 µm British Standard (BS) sieve (Amin and Abdelsalam 2019). Several analytical techniques, including scanning electron microscopy (SEM), thermogravimetric analysis (TGA), X-ray fluorescence (XRF), and X-ray diffraction (XRD), are used to analyze the chemical properties of the RHFA (Amin and Abdelsalam 2019). These methods provide a detailed understanding of ash chemical composition by enabling quantification of various components, phase identification, and surface morphology analysis.

Experimental procedure

A field experiment was conducted at BRRI in Gopalganj, Bangladesh, during the dry season (November-December to April-May). Five popular rice varieties were chosen for this trial. The varieties included BRRI dhan102, BRRI dhan104, BRRI dhan105, BRRI dhan107, and BRRI dhan108 (BRRI 2024). Initially, seeds of different rice varieties were soaked in 30% H_2O_2 for 20 minutes to surface-sterilize them and prevent seed-borne diseases (Biswash et al. 2024a). After soaking, the seeds were thoroughly washed 3–4 times with clean water, then soaked again for 48 hours. They were then placed in a dark plastic container at 27°C to promote proper sprouting (Biswash et al. 2021). After 3 to 4 days, germinated seeds were transferred to a seedbed prepared in a peat-soil area. Thirty-five-day-old seedlings from each variety were planted in 4 m × 5 m plots, with 2–3 seedlings spaced 20 cm × 20 cm apart, following a randomized complete block design (RCBD) with 2 factors (RHFA and rice varieties). Treatments were compared using a block design with 3 replications. A flat dose of N, P, K, S, and Zn at the rates of 270-100-165-112-11(kg/ha), respectively, was applied at urea, triple superphosphate (TSP), muriate of potash (MOP), gypsum, and zinc sulfate (Bangladesh Rice Knowledge Bank, n.d.). The total amounts of TSP, two-thirds of MOP, Gypsum, and $ZnSO_4$ were applied during land preparation. Urea was applied in three equal splits at 15 days after transplanting (DAT), 30 DAT, and 5 days before panicle initiation (PI). The remaining one-third of

MOP was applied with the third urea top dressing. Rice husk fly ash (RHFA) was applied at a rate of 5.0 t/ha during final land preparation (Nelvia 2018). Crop management practices were carefully implemented, including weed control, irrigation, pest and disease control, and rodent control.

Determination of plant growth and yield contributing parameters

Plant growth and yield contributing parameter such as growth duration (GD) (days), plant height (PH) (cm), number of panicles per m^2 (NPM^2), panicle length (PL) (cm), number of filled grains per panicle (NFGP), sterility (%), 1000 gwt (gm), and grain yield (GY) (t/ha) was measured by various procedure such as the growth period was calculated from when the seeds were soaked until the panicle turned yellow or reached 80% maturity. Ten plants were randomly chosen from a plot, and their heights were measured in centimeters from the base to the top of the panicle. The number of filled grains within a panicle indicated the number of effective panicles in each plot. This method was used to count the number of effective panicles per square meter for each variety across all plots. Panicle length was measured by collecting ten randomly selected panicle samples from each plot, starting at the base of the rachis and ending at the tip. Ten panicles were randomly selected from each plot, and the total number of grains in each panicle was manually counted. The average number of grains per panicle was calculated by dividing the total number of grains by 10.

The unfilled grains were also counted from the same panicle from which the whole grains were measured. The sterility percentage was calculated using the total number of grains and the number of unfilled grains per panicle, as shown in the equation below (Biswash et al. 2024b).

$$\text{Sterility } (\%) = \frac{\text{Number of unfilled grains}}{\text{Total number of grains}} x100$$

The weight of 1000 grains was measured with a portable electronic balance, and the moisture content was calculated to be 14%. The unit of measurement for the thousand-grain weight was grams (g).

Harvesting involves collecting the ripened rice from the field. It includes cutting, threshing, cleaning, transportation, and bagging. Harvest should be done when 80–85% of the grains are ripe (i.e., turned yellow) or when the grain moisture content is between 18% and 23%. Use the following formula to convert the grain weight from the net harvest area to a 14% moisture content (Biswash et al. 2024b).

$$\text{Grain weight at 14\% moisture } = \frac{\text{Grain weight (g)} \times [100 - \text{Grain moisture content (\%)}}{86}$$

Statistical analysis

Microsoft Excel 365 (Version 16.0) (Excel 2024), STAT 10, and R software were used for all statistical analyses and data processing. A two-way analysis of variance (ANOVA) with Duncan's multiple range test was conducted in Statistix 10 to examine differences among treatments at the $P < 0.05$ level of significance (Biswash et al. 2024b). Additionally, the R software's "FactoMineR" package was used to perform Principal Component Analysis (PCA) to assess relationships among RHFA effects on peat soil across different rice varieties (Verma et al. 2025).

Results

Chemical properties of the rice husk fly ash (RHFA)

The laboratory investigation revealed that the pH of the rice husk fly ash (RHFA) and the moisture content were 7.32 and 6.46, respectively. RHFA is especially rich in SiO_2 (85%). The macronutrients P, K, S, and Ca in the RHFA were 0.92%, 2.25%, 0.28%, and 0.44%, respectively. The micronutrient levels, including Mg, Fe, and Zn, were 0.20%, 0.03%, and 0.052%, respectively. Here, the functional nutrient or beneficial element (Na) was 0.85% (Table 1). Table 1 presents the basic chemical properties and their corresponding values for rice husk fly ash (RHFA).

Table 1
The chemical properties and moisture content of rice husk fly ash (RHFA).

Component	Moisture (%)	pH	SiO_2 (%)	P(%)	K(%)	S(%)	Ca(%)	Mg(%)	Na(%)	Fe(%)	Zn(%)
Value	6.46	7.32	85	0.92	2.25	0.28	0.44	0.20	0.85	0.03	0.05

Note: SiO_2: Silicon dioxide; P: Phosphorus; K: Potassium; S: Sulfur; Ca: Calcium; Mg: Magnesium; Na: Sodium; Fe: Iron; Zn: Zinc

Chemical properties of the initial and harvested peat soil

Applying RHFA to peat soil significantly changed the soil chemical properties. The soil's pH increased from 5.41 (moderately acidic) to 6.84 (nearly neutral), and the soil salinity changed from 4.30 dS/m (slightly saline) to non-saline or moderately saline (2.52 dS/m). Organic matter (OM) increased from 9.58% to 11.45%. Not only that, after the application of RHFA, the availability of macronutrients such as total N%, P, K, Ca, Mg, and S was changed from 0.46 to 0.65 (both were very high), 5.30 (low) to 7.15 (medium), 0.46 (medium) to 0.64 (high), 10.30 (high) to 16.43 (very high), 5.0 to 5.71 (both were high), and 220 to 266 (both were very high), respectively (Table 2). The micronutrient availability of Zn, B, Cu, Fe, and Mn in the soil changed from 1.81 (high) to 2.71 (very high), 0.65 (medium) to 0.39 (low), 5.48 to 7.73 (both were high), 10.27 (medium) to 21.68 (high), and 1.15 (low) to 2.85 (medium), respectively (Table 2). Table 2 presents the chemical properties of the peat soil before and after applying rice husk fly ash (RHFA) to the soil.

Table 2
The chemical properties of the peat soil before and after the application of rice husk fly ash (RHFA) to the soil.

Chemical properties of peat soil	pH	Salinity (ds^{-1})	*OM	N (%)	P (µg/g)	K (meq 100 g^{-1})	Ca (meq 100 g^{-1})	Mg (meq 100 g^{-1})	S (µg 1000 g^{-1})	Zn (µg/g)	B (µg 1000 g^{-1})	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)
Before RHFA application	5.41	4.30	9.58	0.46	5.30	0.46	10.30	5.00	220	1.81	0.65	5.48	10.27	1.15
After RHFA application	6.84	2.52	11.45	0.65	7.15	0.64	16.43	5.71	266	2.71	0.39	7.73	21.68	2.85
*OM: Organic matter														

Physiological changes of different dry-season rice varieties grown in peat soil with and without rice husk fly ash (RHFA)

Application of RHFA on peat soil showed significant variation in plant growth and yield-contributing parameters across five rice genotypes, including growth duration (GD), plant height (PH), number of panicles per m^2 ($NFPM^2$), sterility %, 1000-grain weight (1000 gwt) for four varieties, and number of filled grains per panicle (NFGP) for one variety, whereas panicle length (PL) showed non-significant variation. A significant increase in grain yield (GY) was also observed.

Effect of rice husk fly ash (RHFA) on rice growth duration (days) of rice varieties grown in peat soil

Growth duration differed significantly among the evaluated rice varieties after RHFA application in peat soil (Table 3). In general, RHFA slightly prolonged the growth duration of all varieties compared with the untreated control. Among the rice varieties, BRRI dhan101 exhibited the greatest response, with its growth duration increasing from 144 to 146 days, representing a 1.39% increase. In contrast, BRRI dhan102, BRRI dhan104, BRRI dhan105, and BRRI dhan108 each showed a one-day increase in growth duration, corresponding to increases of 0.68%, 0.69%, 0.68%, and 0.68%, respectively. The longest growth duration (149 days) was observed in BRRI dhan108 with RHFA-treated soil, while the shortest growth duration (144 days) was recorded in BRRI dhan101 in non-RHFA peat soil. Although the increase in growth duration was relatively small (1–2 days), the consistent response across all rice varieties indicates that RHFA positively influenced crop development in peat soil. Based on the percentage increase in growth duration (days) across the different rice varieties, the order followed was: BRRI dhan101 > BRRI dhan104 > BRRI dhan102 = BRRI dhan105 = BRRI dhan108.

Table 3
Three growth parameters are represented in five dry-season rice varieties

Growth parameters	GD (days)		PH (cm)		NPM^2	
Varieties	Without RHFA	With RHFA	Without RHFA	With RHFA	Without RHFA	With RHFA
BRRI dhan101	144	146	118.0	119.5	296	329
BRRI dhan102	146	147	105.5	109.7	351	380
BRRI dhan104	145	146	109.0	110.0	348	375
BRRI dhan105	147	148	111.7	112.5	330	380
BRRI dhan108	148	149	103.5	108.5	313	349
Lsd (0.05)	0.92	0.40	3.92	1.72	20.10	8.4
CV	0.36		2.03		3.34	

Effect of rice husk fly ash (RHFA) on rice plant height (cm) of rice varieties grown in peat soil

Plant height (cm) was significantly influenced by the application of RHFA in peat soil (Table 3). Among the five rice varieties, plant height increased following RHFA application, although the magnitude of the response varied among genotypes. The tallest plant was observed in BRRI dhan101 under RHFA-treated soil at 119.5 cm, while the shortest plant growth was in BRRI dhan108 at 103.5 cm, in RHFA-non-treated soil. Plant height of BRRI dhan101 increased from 118.0 to 119.0 cm (1.27%), while BRRI dhan102 increased from 105.5 to 109.7 cm (3.95%). Similarly, BRRI dhan104, BRRI dhan105, and BRRI dhan108 exhibited increases from 109.0 to 110.0 cm (0.92%), 111.0 to 112.5 cm (1.35%), and 103.5 to 108 cm (4.83%), respectively. On the basis of the percent increase in plant height (cm) among the different rice varieties, ranked from highest to lowest as follows: BRRI dhan108 > BRRI dhan102 > BRRI dhan105 > BRRI dhan101 > BRRI dhan104.

Effect of rice husk fly ash (RHFA) on the number of panicles per m² (NPM2) of rice varieties grown in peat soil

Application of RHFA significantly increased the number of panicles per m² in all evaluated rice varieties grown in peat soil (Table 3). The positive response was evident across all genotypes, although the magnitude of the increase differed among varieties. Without RHFA, the number of panicles per m² (NPM2) ranged from 296 in BRRI dhan101 to 351 in BRRI dhan102. Following RHFA application, the NPM2 increased to 329, 380, 375, 380, and 349 in BRRI dhan101, BRRI dhan102, BRRI dhan104, BRRI dhan105, and BRRI dhan108, respectively. Among the tested varieties, BRRI dhan105 showed the greatest improvement, with NPM2 increasing from 330 to 380 panicles per m², a 15.05% increase over the RHFA non-treated soil. This was followed by BRRI dhan108 (11.52%), BRRI dhan101 (11.15%), BRRI dhan102 (8.21%), and BRRI dhan104 (7.77%), respectively. The highest number of panicles per m² was observed at 380 in the BRRI dhan102 and BRRI dhan105 rice varieties with RHFA-treated soil, while the lowest was 296 in BRRI dhan101 without RHFA application. Based on the percentage increase in NPM^2 among these varieties, ranked as follows (highest to lowest): BRRI dhan105 > BRRI dhan108 > BRRI dhan101 > BRRI dhan102 > BRRI dhan104.

Effect of rice husk fly ash (RHFA) on the number of filled grains per panicle (NFGP) of rice varieties grown in peat soil

The application of rice husk fly ash (RHFA) significantly increased the number of filled grains per panicle (NFGP) due to the RHFA application in peat soil (Fig. 1). Under the control treatment (without RHFA), the total NFGP ranged from 111 in BRRI dhan104 to 227 in BRRI dhan108. Following RHFA application, the NFGP increased from approximately 143 to 153 grains $panicle^{-1}$ in BRRI dhan101, from 115 to 121 grains $panicle^{-1}$ in BRRI dhan102, from 111 to 135 grains $panicle^{-1}$ in BRRI dhan104, from 136 to 148 grains $panicle^{-1}$ in BRRI dhan105, and from 227 to 243 grains $panicle^{-1}$ in BRRI dhan108, respectively. Among the tested rice varieties, BRRI dhan104 exhibited the greatest response to RHFA, with the NFGP (21.48%) exceeding that of the RHFA-non-treated soil. This was followed by BRRI dhan105 (8.44%), BRRI dhan108 (7.32%), BRRI dhan101 (6.74%), and BRRI dhan102 (5.91%). Based on the percentage increase across the rice varieties, the ranking was as follows: BRRI dhan104 > BRRI dhan105 > BRRI dhan108 > BRRI dhan101 > BRRI dhan102.

Effect of rice husk fly ash (RHFA) on panicle length (PL) (cm) of rice varieties grown in peat soil

The application of RHFA positively influences panicle length (cm) across all rice varieties in peat soil compared with RHFA-non-treated soil (Fig. 2). Under the control treatment (without RHFA), panicle length ranged from 23.5 cm in BRRI dhan105 to 24.2 cm in both BRRI dhan102 and BRRI dhan104. Following RHFA application, panicle length increased to 24.5, 25.5, 25.0, 24.3, and 25.2 cm in BRRI dhan101, BRRI dhan102, BRRI dhan104, BRRI dhan105, and BRRI dhan108, respectively. Among the evaluated varieties, BRRI dhan102 showed the greatest increase in panicle length, rising from 24.2 to 25.5 cm, a 5.23% increase over the control (without RHFA). This was followed by BRRI dhan108 (4.85%), BRRI dhan101 (3.52%), BRRI dhan105 (3.40%), and BRRI dhan104 (3.31%). Based on the percentage increase across the rice varieties, the ranking was as follows: BRRI dhan102 > BRRI dhan108 > BRRI dhan101 > BRRI dhan105 > BRRI dhan104.

Effect of rice husk fly ash (RHFA) on sterility (%) of rice varieties grown in peat soil

The application of RHFA significantly reduced sterility (%) across all evaluated rice varieties grown in peat soil (Fig. 3). This reduction indicates that RHFA improves grain filling and reproductive efficiency under peat soil conditions. Without RHFA application, the sterility (%) ranged from 14% in BRRI dhan102 to 29% in BRRI dhan104. Following RHFA application, the sterility% decreased to 21%, 12%, 20%, 15%, and 23% in BRRI dhan101, BRRI dhan102, BRRI dhan104, BRRI dhan105, and BRRI dhan108, respectively. Among the tested varieties, BRRI dhan105 exhibited the greatest reduction in sterility from 22% to 15%, corresponding to a 32% reduction. Similarly, BRRI dhan104 showed a 31% reduction, followed by BRRI dhan101 (25%), BRRI dhan108 (18%), and BRRI dhan102 (14%). Although BRRI dhan102 had the lowest sterility % under both control (without RHFA) and RHFA-treated conditions, BRRI dhan105 and BRRI dhan104 still showed the greatest relative improvement after RHFA application. Based on the percentage reduction in sterility (%) across the rice varieties, the varieties ranked as follows: BRRI dhan105 > BRRI dhan104 > BRRI dhan101 > BRRI dhan108 > BRRI dhan102.

Effect of rice husk fly ash (RHFA) on 1000-grain weight (gwt) (gm) of rice varieties grown in peat soil

The application of RHFA in peat soil significantly increased the 1000-grain weight of all evaluated rice varieties grown in peat soil compared with the non-treated RHFA soil (Fig. 4). Although the magnitude of improvement varied among the rice varieties, RHFA consistently enhanced

grain weight compared with the untreated control, indicating its beneficial effect on grain development and grain filling. In untreated soil, 1000 gwt ranged from 17.2 to 24.8 gm, whereas RHFA application increased 1000 gwt to 18.0 to 25.4 gm. Following RHFA application, the 1000-gwt increased to 24.1, 23.5, 25.4, 21.0, and 18.0 gm in BRRI dhan101, BRRI dhan102, BRRI dhan104, BRRI dhan105, and BRRI dhan108, respectively. Among the evaluated varieties, BRRI dhan102 exhibited the greatest relative increase in 1000 gwt, increasing from 22.4 to 23.5 gm, corresponding to a 4.91% increase over the control. BRRI dhan108 also showed a marked improvement (4.72%), followed by BRRI dhan105 (4.11%), BRRI dhan101 (3.09%), and BRRI dhan104 (2.18%). Although the highest 1000 gwt was observed in BRRI dhan104 at 24.8 gm without RHFA-treated soil, with RHFA application it increased to 25.4 gm, while BRRI dhan102 exhibited the greatest responsiveness to RHFA application in peat soil. Based on the percentage increase across the rice varieties, the ranking as follows: BRRI dhan102 > BRRI dhan108 > BRRI dhan105 > BRRI dhan101 > BRRI dhan104.

Effect of rice husk fly ash (RHFA) on grain yield (t/ha) across dry-season rice varieties

The application of RHFA positively influenced grain yield (t/ha) across all BRRI dry-season rice varieties (Fig. 5). Without RHFA-treated soil, grain yields of all rice varieties ranged from 7.0 to 8.7 t/ha, whereas RHFA application increased yields to 8.6–9.4 t/ha. The highest grain yield was recorded at BRRI dhan108 at 9.4 t/ha in RHFA-treated soil. Under the same field conditions, the lowest grain yield was recorded in BRRI dhan102 at 8.6 t/ha (Fig. 5). Without RHFA application in peat soil, the highest grain yield was recorded in BRRI dhan105 at 8.7 t/ha, and the lowest in BRRI dhan104 at 7.0 t/ha. The highest response to RHFA was observed in BRRI dhan104, which showed a 1.7-unit increase (24.4%) in grain yield over non-treated soil. The percentage increases in grain yield for other rice varieties, such as BRRI dhan101, BRRI dhan102, BRRI dhan105, and BRRI dhan108, in RHFA-treated soil were 10.91%, 6.11%, 4.51%, and 10.13%, respectively. The varieties showed the following order of grain yield percentage, from highest to lowest: BRRI dhan104 > BRRI dhan101 > BRRI dhan108 > BRRI dhan102 > BRRI dhan105.

Principal component analysis (PCA) of various yield-contributing parameters across different rice varieties

Principal Component Analysis (PCA) showing relationships among rice yield and yield-contributing parameters under both conditions: with and without RHFA application in peat soil. The first principal component (Dim 1) explained 35.9% of the total variation, and the second (Dim 2) accounted for 29.2%. Together, they explained 65.1% of the total variability across the measured parameters, indicating that PCA effectively summarized the experimental data (Fig. 6). The vectors in the biplot represent the contributions and correlations of individual parameters. Parameters such as number of effective tillers per m^2 (NPM2), panicle length (PL), grain yield (GY), growth duration (GD), and number of filled grains per panicle (NFGP) were positively associated with the RHFA treatment, as indicated by their orientation toward the cluster of RHFA-treated samples. This suggests that adding RHFA enhances growth- and yield-related parameters, thereby improving rice productivity (Fig. 6). The small angle between the GY and GD parameters indicates a strong positive correlation, implying that growth duration directly contributes to higher grain yield. Similarly, the proximity of the PL and NPM^2 parameters suggest a positive association between panicle length and panicle-related characteristics that ultimately affect higher grain yield.

In contrast, sterility (%) and plant height (PH) were positioned in the opposite direction from the RHFA-associated grain yield parameters, indicating a negative correlation. This suggests that higher sterility and plant height reduced grain yield and overall productivity. Without the RHFA application, the peat soil was more associated with higher sterility and lower yield performance compared with the RHFA-treated soil. The 1000 gwt parameter was positioned separately toward the negative side of Dim1, indicating that it contributed independently to variation among treatments and varieties. Its moderate distance from the grain yield parameters suggests that, although grain weight influences yield, it was less strongly associated with yield than filled grain percentage and other yield-contributing parameters.

Note

GD: Growth duration (days), NFGP: Number of Filled Grains Per Panicle, PL: Panicle length (cm), NPM2: Number of Panicles per m^2, Sterility%: Sterility (%) of each variety, 1000gwt: 1000 grain weight (gm), GY: Grain yield (t/ha).

Discussion

RHFA contains a higher amount of silica (Table 1). Silica absorption fortifies the plant's cell walls, providing inherent protection against pests, fungal infections, and lodging (Huang and Ma 2024; Verma et al. 2024). RHFA helps increase the pH of peat soil, releasing locked phosphorus (P) and potassium (K) and allowing rice roots to absorb P and K more easily (Muharram et al. 2025). In the peat soil, H^+ ions hydrolyzed the RHFA, leading to its rapid disintegration. Due to H^+ ion dissociation from organic molecules, the H^+ ion concentration in the peat soil was relatively high (Nelvia et al. 2018). Therefore, RHFA can improve nutrient availability in peat soil for dry-season rice varieties, promoting better plant growth and higher yields. The concentrations of macronutrients and micronutrients in the RHFA followed the order: K > P > Ca > S > Mg > Zn > Fe, respectively. Nitrogen (N) is the most limiting nutrient element for plant growth: Peat soil contained very high levels of total nitrogen (N), organic matter, and organic carbon (C). However, the elevated C/N ratio suggested slow organic matter decomposition and enhanced microbial nitrogen immobilization, which limited nitrogen mineralization into plant-available forms. Consequently, nitrogen availability and plant

uptake were reduced, adversely affecting plant growth (Li et al. 2026). According to Manalu et al. (2024) and Suryandi et al. (2023), peat soil generally has limited availability of macronutrients (N, P, K, Ca, and Mg) and micronutrients (Cu, Zn, Mn, Fe, B, and Mo), which is consistent with the findings of the present study. Without RHFA application, the peat soil had a low pH and was moderately saline. With RHFA application, soil pH shifted toward near-neutral conditions, indicating the liming effect of rice husk fly ash on acidic peat soils (Muharram et al. 2025). Not only that, RHFA-treated soil, the pH increased by approximately 1.43 units, and salinity decreased by 1.78 dS/m (Table 2). This may be because, over time, organic matter decomposes and mixes with the soil, thereby improving its structure, porosity, and drainage characteristics (Brady and Weil 2022). This process reduces the electrical conductivity (EC) and sodium adsorption ratio (SAR) in the peat soil, ultimately lowering its salinity (dS/m). Similar results were also reported by Babazad et al. (2021) and Singh et al. (2017). Essential plant nutrients such as total N, P, K, Ca, Mg, S, Zn, Cu, Fe, and Mn also increased by 0.19, 1.85, 0.18, 6.13, 0.71, 46, 0.9, 2.25, 11.41, and 1.7 times, respectively, compared to conditions without RHFA application, except B (-0.26). Sahin et al. (2024) and Teutscherov et al. (2023) reported similar findings (Table 2). These researchers observed that applying RHFA to peat soil reduces nitrogen losses and increases silicon content and alkaline properties, potentially leading to boron adsorption and fixation, decreasing its availability to plants. Nevertheless, the RHFA can boost nutrient availability and improve soil properties, both of which are crucial for grain growth (Gu et al. 2024). These findings support the results of Kordi et al. (2024) and Nzereogu et al. (2023), which show that RHFA application increases soil pH, exchangeable potassium (K), magnesium (Mg), available phosphorus (P), porosity, organic matter (OM), and plant-available water (PAW).

RHFA significantly affected the rice growth duration (days) of each dry-season rice variety ($P < 0.05$) (Table 3). RHFA application increases the availability of macro- and micro-nutrients in the soil (Gu et al. 2024; Nzereogu et al. 2023), thereby improving the nutrient uptake capacity of rice roots and accelerating plant growth. The growth and development of the rice plant, as well as its growth duration, are directly influenced by the physical traits of its roots (Li et al. 2021), as roots enable the plant to absorb nutrients and water effectively (Driesen et al. 2020). One reason is that applying RHFA with inorganic fertilizer to peat soil resulted in a slightly longer growth period than inorganic fertilizer alone. RHFA significantly affected plant height (cm) across all dry-season rice varieties ($P < 0.05$) (Table 3). Applying RHFA to peat soil significantly increased rice plant height. Similar findings were reported by Teutscherov et al. (2023), they observed that applying RHFA to soil reduces N losses in peat and increases Si availability, enhancing plant height and improving lodging tolerance (Jiang et al. 2025). RHFA significantly influenced the number of effective panicles per m^2 for each dry season rice variety ($P < 0.05$) (Table 3). According to this data, the percentage of effective panicles per m^2 increased in RHFA-treated peat soil compared with peat soil without RHFA application. By boosting biomass production, adding RHFA to peat soil can improve plant growth, particularly by increasing the number of effective tillers per square meter (Nelvia et al. 2018). This advantage likely stems from RHFA's ability to enhance soil properties and nutrient availability.

RHFA significantly affected the number of filled grains per panicle (NFGP) (Fig. 1), which enhances rice yields because RHFA enriches beneficial nutrients, particularly Si, K, Ca, Mg, and P, that promote photosynthesis and delay leaf senescence, thereby increasing the percentage of filled grains and overall grain yield (Gu et al. 2024; Lai et al. 2024). According to the Velasco et al. (2026) reported, the application of silicon during the reproductive stage significantly improved photosynthesis and grain yield. Additionally, using RHFA not only boosts crop yields but also promotes sustainable farming practices by recycling waste materials. This approach benefits farmers economically and reduces environmental impact, making it a promising strategy for future rice production.

RHFA has significantly influenced the panicle length (cm) of each dry-season rice variety (Fig. 2). RHFA plays a role in peat soil, where rice roots have a greater capacity to absorb and utilize the nutrients and silicon supplied by the amendment, thereby increasing rice panicle length (Munda et al. 2016). Some research suggests that adding RHFA to soil may increase shoot length (Jiang et al. 2025; Teutscherov et al. 2023), which is associated with longer panicles. This increase in shoot length can ultimately boost yields, making RHFA a valuable soil amendment for rice farming. Additionally, this agricultural by-product promotes sustainable agriculture by recycling waste.

RHFA significantly affected the spikelet sterility (%) of each dry-season rice variety (Fig. 3). RHFA is a rich source of plant-available silicon and several essential nutrients that enhance physiological function, strengthen antioxidant defenses, and support reproductive development during the flowering stage (Shi et al. 2022). RHFA ultimately improves peat soil properties and nutrient availability, promoting grain development, reducing unfilled grains, and lowering the sterility percentage (Lai et al. 2024). These findings are consistent with previous studies reporting that spikelet sterility in rice is highly sensitive to reproductive-stage stress and that improved physiological protection can enhance seed set (Shi et al. 2022). However, not all rice cultivars are equally affected by RHFA; some respond more strongly than others. This variation may be due to genetic differences among cultivars that influence their ability to use the improved soil properties provided by RHFA.

RHFA significantly affected the 1000-gwt (g) of each dry-season rice variety (Fig. 4). The rice plants absorb more nutrients due to the altered soil characteristics caused by RHFA, which could increase the 1000-gwt (Gu et al. 2024). RHFA is rich in soluble Si, K, Ca, and other mineral nutrients that enhance plant physiological activities. Silicon improved leaf erectness, photosynthetic efficiency, nutrient uptake, and assimilate translocation, thereby enhancing reproductive development and grain formation (Velasco et al. 2026). According to Nelvia (2018), organic amendments such as RHFA are combined with inorganic fertilizer and applied to peat soil; rice grain weight increases significantly compared

with peat soil treated with inorganic fertilizer alone. The current study provides evidence supporting this claim. This suggests that combining organic and inorganic amendments may synergistically enhance plant growth and yield.

RHFA significantly influenced the grain yield (t/ha) of each dry season rice variety ($P < 0.05$) (Fig. 5). This finding supports the results of Kordi et al. (2024); Nzereogu et al. (2023), and Okoro et al. (2022), showing that RHFA application improves soil chemical and physical properties in cropland, which enhances soil pH, exchangeable potassium (K), magnesium (Mg), available phosphorus (P), porosity, organic matter (OM), and plant-available water (PAW) (Gu et al. 2024). Based on these soil properties, RHFA promotes plant root development and increases plants' nutrient-absorption capacity in peat soils.

The PCA biplot shows that applying RHFA to peat soil positively influenced rice growth and yield-related parameters (Fig. 6). The RHFA treatment was closely associated with higher grain yield, improved panicle characteristics, and reduced sterility, highlighting its beneficial role in enhancing rice productivity. Our findings are consistent with those findings such as Jiang et al. (2025); Gu et al. (2024); Kordi et al. (2024); Lai et al. (2024); Nzereogu et al. (2023); Teutscherov´ et al. (2023); Nelvia, (2018); Okoro et al. (2022).

Conclusion

RHFA has an elevated silica concentration that strengthens the plant's cell walls, offering intrinsic defense against pests and fungal diseases and improving lodging tolerance. Because of its high silica content and porous particles, RHFA enhances soil aggregation and porosity. Soil structure plays a crucial role in water infiltration and drainage, which, in turn, enables the leaching of excess soluble salts below the root zone. Incorporating RHFA improves peat soil by reducing nitrogen loss and enhancing its physical properties through increased soil organic matter. Neutral soil pH plays an important role in reducing nitrogen loss in RHFA-amended peat soils. PCA explained 65.1% of the total variability in the measured parameters, summarizing experimental data from both untreated and RHFA-treated peat soil across different dry-season rice varieties. Using RHFA increases the availability of macro- and micronutrients in peat soil, which directly affects rice growth and grain yield components, including the number of panicles per m^2 (NPM^2), panicle length (PL), grain yield (GY), growth duration (GD), and number of filled grains per panicle (NFGP). These five parameters show a strong positive correlation. Other parameters, such as 1000 gwt, sterility (%), and plant height (PH), show negative correlations with RHFA-treated soil. When both field conditions were considered, the BRRI dhan108 variety produced the highest grain yield. BRRI dhan108 also showed the highest GD, the highest increase in PH, the highest NFGP, and the lowest 1000gwt. Additionally, RHFA increases the water-holding capacity of peat soil, reducing irrigation costs for farmers. It also serves as a soil amendment that improves soil chemical, physical, and biological properties. Consequently, it is likely to significantly increase dry-season rice production in Gopalganj of Bangladesh.

Declarations

Conflict of interest

The authors declare no conflict of interest.

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Author contributions

Md. Romel Biswash: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization; Khondoker Khalid Ahmed: Formal analysis; Md Hymun Kabir Baktier: Investigation, Formal analysis; Umme Aminun Naher: Conceptualization, Writing – review & editing; Amina Khatun: Supervision, Investigation, Funding acquisition, Conceptualization; Md Habibur Rahman Mukul: Methodology, Investigation; Md. Imran Hossain: Formal analysis; Ernest Uwiringiyimana: Conceptualization, Formal analysis; Ren-kou Xu: Conceptualization, manuscript review & editing.

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Data availability

The article contains data that supports the research's conclusions. Any additional details will be sent to the corresponding author upon request.

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Figures

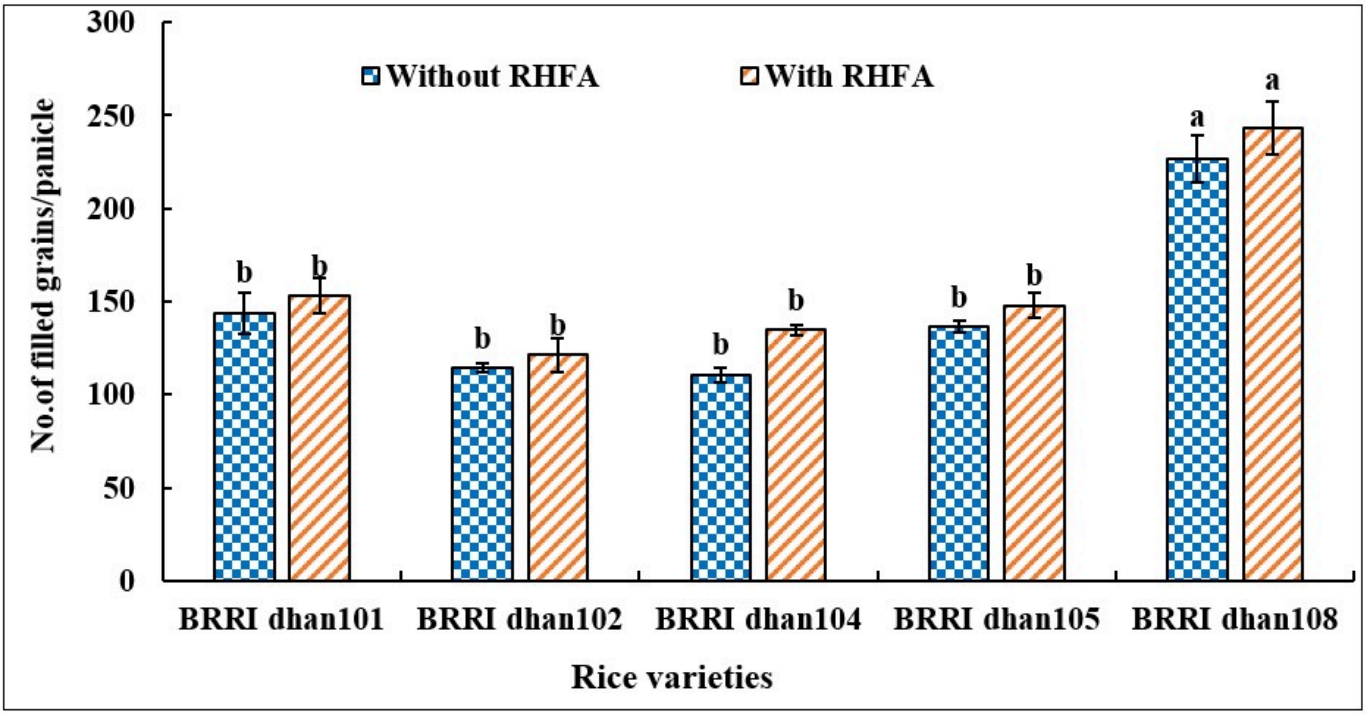


Figure 1

Changes in the no. of filled grains/panicle among different rice varieties before and after rice husk fly ash (RHFA) application. Error bars represent the standard errors of the means (n=5). Lowercase letters within the bar graph denote significant differences among treatments as determined by Duncan's multiple-range test at the 0.05% level of significance.

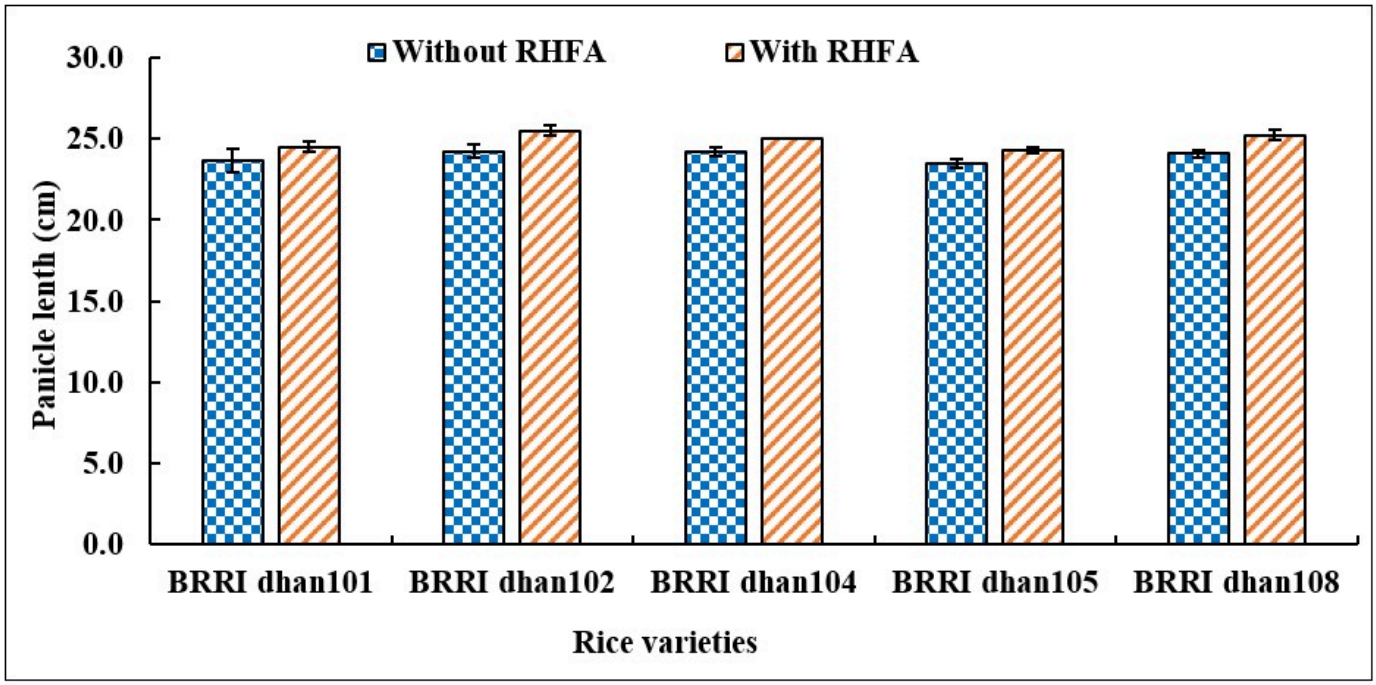


Figure 2

Changes in the panicle length (cm) among different rice varieties before and after rice husk fly ash (RHFA) application. Error bars represent the standard errors of the means (n=5). There were no significant differences among the treatments as determined by Duncan's multiple-range test at the 0.05% level of significance.

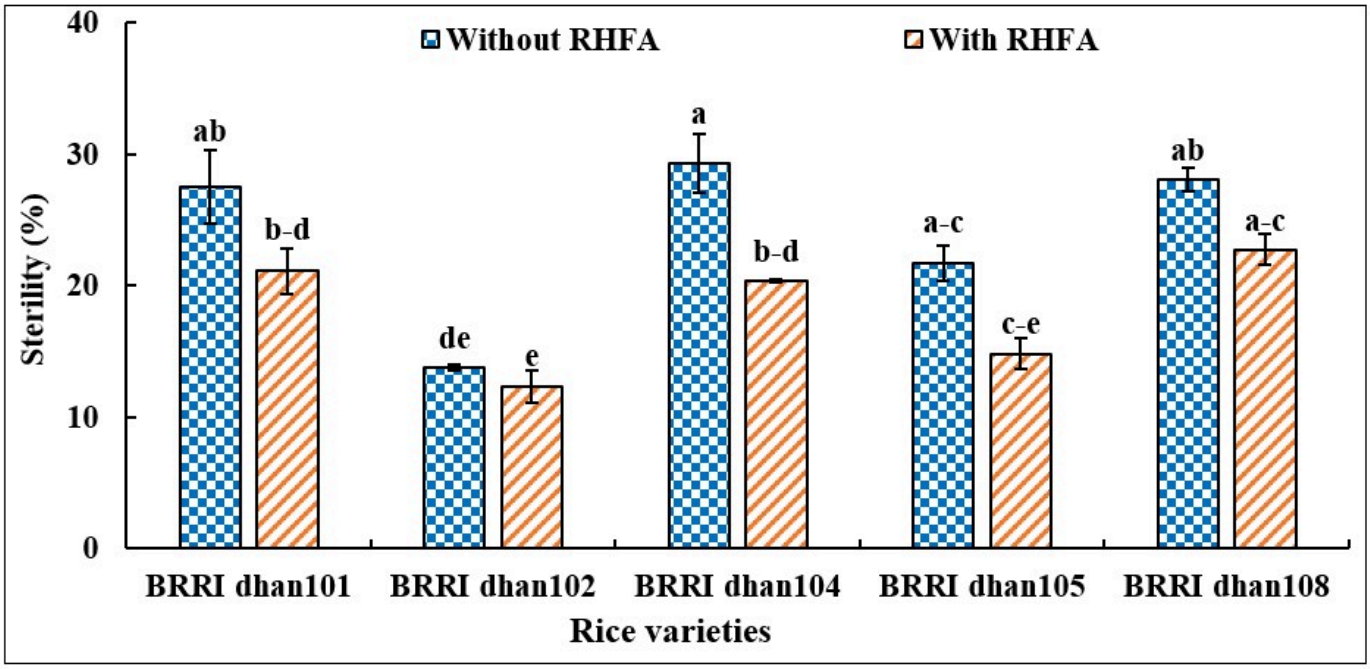


Figure 3

Changes in sterility (%) among different rice varieties with and without rice husk fly ash (RHFA) application. Error bars represent the standard errors of the means (n=5). Lowercase letters within the bar graph denote significant differences among treatments as determined by Duncan's multiple-range test at the 0.05% level of significance.

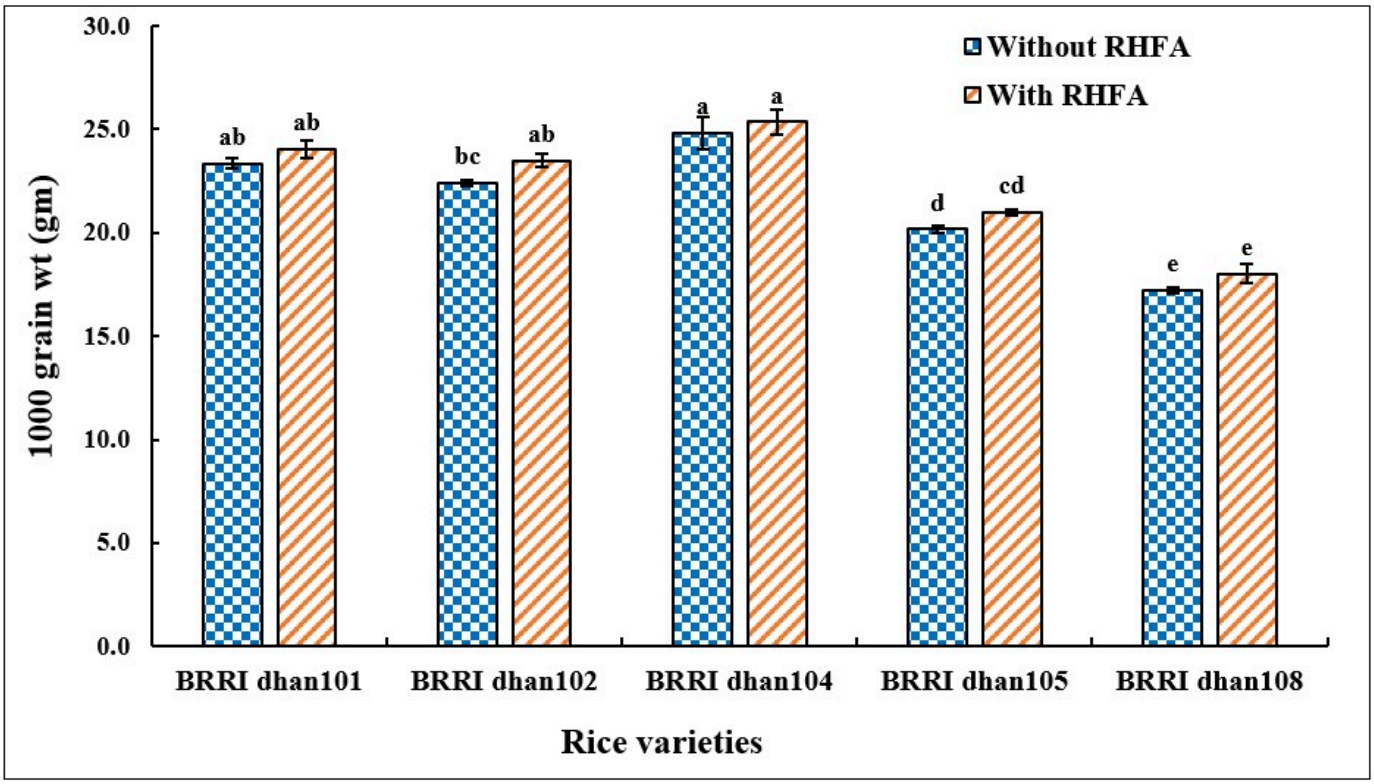


Figure 4

Changes in the 1000 gwt (gm) among different rice varieties with and without rice husk fly ash (RHFA) application. Error bars represent the standard errors of the means (n=5). Lowercase letters within the bar graph denote significant differences among treatments as determined by Duncan's multiple-range test at the 0.05% level of significance.

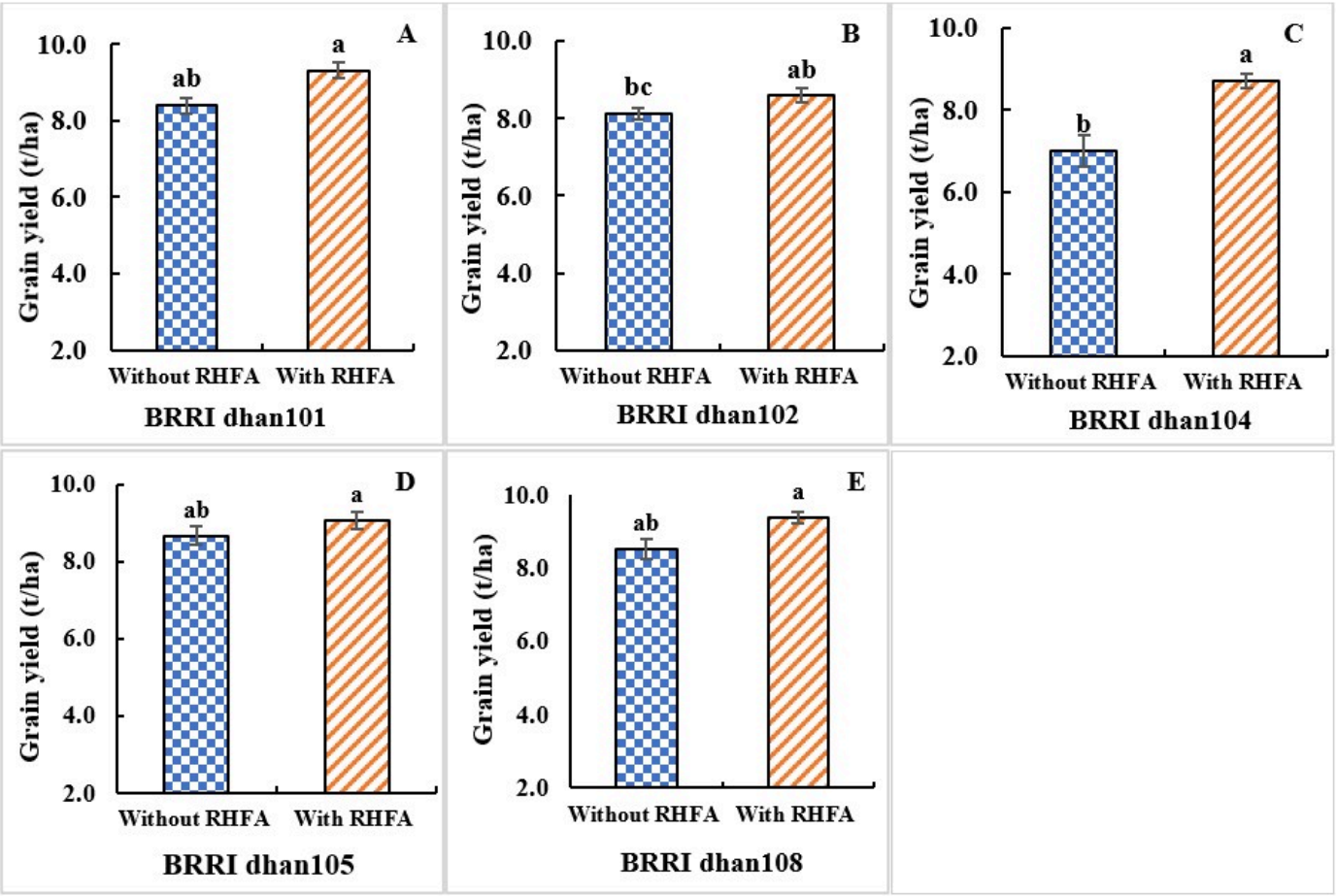


Figure 5

Changes in the grain yield among different rice varieties with and without rice husk fly ash (RHFA) application. Error bars represent the standard errors of the means (n=5). Lowercase letters within the bar graph denote significant differences among treatments as determined by Duncan's multiple-range test at the 0.05% level of significance.

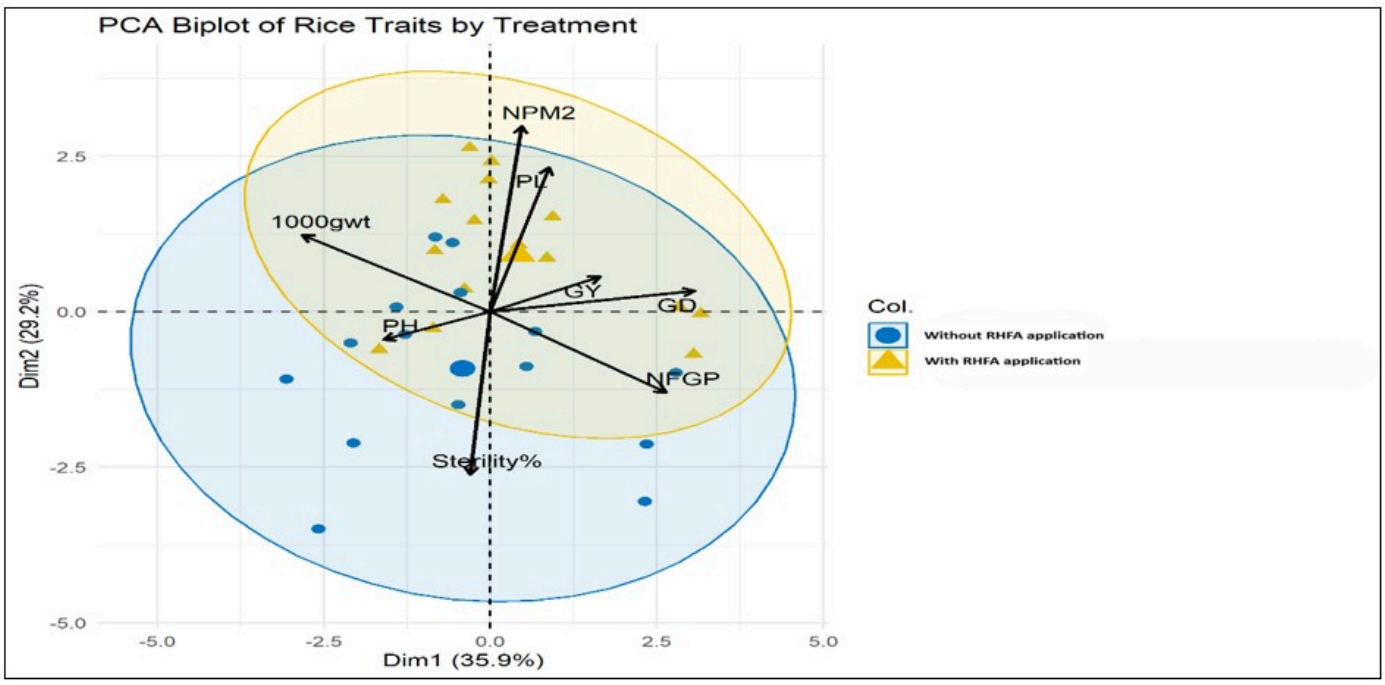


Figure 6

Principal component analysis (PCA) of various rice yield components or parameters.

Note: GD: Growth duration (days), NFGP: Number of Filled Grains Per Panicle, PL: Panicle length (cm), NPM2: Number of Panicles per m^2, Sterility%: Sterility (%) of each variety, 1000gwt: 1000 grain weight (gm), GY: Grain yield (t/ha).

Supplementary Files

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