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Combined Effect of Seed Priming and Organic Amendments on the Agronomic Output of Dry Direct-Seeded Winter Rice in Floodplain Soil of Bangladesh

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Abstract

Rice production in the floodplain ecosystems of Bangladesh is increasingly constrained by water scarcity and declining soil fertility, necessitating sustainable and efficient management practices. This study evaluated the effects of seed priming and organic amendments on the growth, yield, water use efficiency, and soil health of dry direct-seeded winter rice (BRRI dhan88). A two-year field experiment (2023 to 2024) was conducted using 3 priming techniques: hydro-priming, halo-priming ($CaCl_2$), and osmo-priming (PEG 6000 w/v) in combination with organic amendments, particularly vermicompost, alongside recommended fertilizer doses. The experiment was laid out in a randomized complete block design (RCBD) with 3 replications. The total number of plots was 48. Growth traits, yield components, irrigation use, and post-harvest soil properties were measured, and multivariate analyses were conducted to assess relationships among traits. Seed priming significantly improved plant growth and yield compared to unprimed seeds. Hydro-priming produced the highest grain yield (5.73 tons ha^{-1}), exceeding the control (4.08 tons ha^{-1}). Organic amendments, especially vermicompost, further enhanced performance, with recommended fertilizer doses (RDF)+vermicompost yielding 5.60 tons ha^{-1}. Their combined application improved grain yield, reaching up to 6.67 tons ha^{-1}. Organic amendments also reduced irrigation water use by up to 27%, indicating improved water use efficiency. Soil properties improved, with higher organic matter, nutrient content, and balanced pH. Overall, integrating seed priming with organic amendments, particularly vermicompost, offers a practical and sustainable approach to enhance rice productivity, conserve water, and improve soil fertility under water-limited conditions.

Keywords: direct seeding; dry direct-seeded rice; floodplain agroecosystem; vermicompost; zero tillage

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INTRODUCTION

Rice (*Oryza sativa* L.) is a major staple crop that supports global food security and the livelihoods of millions of smallholder farmers, particularly in Asia (Mohapatra et al., 2025). Globally, rice is cultivated on approximately 163 million hectares, producing around 510 million tons annually (Darko et al., 2025). Its importance is particularly pronounced in Bangladesh, where rice accounts for nearly 95% of total food-grain production and forms the foundation of national food security and rural livelihoods (Saha et al., 2021; Mia et al., 2023). With annual production exceeding 38 million tons, Bangladesh is also among the world's

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leading rice-producing countries (Chowhan et al., 2024).

Among Bangladesh's 3 major rice-growing seasons, pre-monsoon (*Aus*), monsoon (*Aman*), and winter (*Boro*), winter rice plays a particularly important role in ensuring national food security (Siddika et al., 2024; Islam et al., 2025). Cultivated from November to May under predominantly irrigated conditions, winter rice generally achieves higher yields because of favorable temperatures, solar radiation, and crop management conditions (Rahman et al., 2025). However, its production is still largely dependent on conventional puddled transplanted rice (PTR), a system that requires substantial water, labor, and energy inputs. Seasonal irrigation requirements may reach 1,500 to 2,000 mm, while groundwater depletion, labor shortages, and increasing production costs are placing growing pressure on the sustainability of conventional rice production (Singh et al., 2022). These challenges emphasize the need for alternative establishment methods that can maintain productivity while reducing resource requirements.

Dry direct-seeded rice (DDSR) has emerged as a promising climate-smart alternative to PTR (Sandhu et al., 2021a). In DDSR, seeds are sown directly into dry or moist, non-puddled soil, eliminating nursery raising, puddling, and transplanting operations (Chaudhary et al., 2023). This approach can reduce irrigation water use by approximately 40 to 70% compared with conventional continuously flooded systems. It can also reduce labor requirements and potentially shorten crop duration by 7 to 10 days, thereby facilitating earlier establishment of subsequent crops (Sandhu et al., 2021b; Ishfaq et al., 2022). Furthermore, the more aerobic soil conditions associated with DDSR may reduce methane emissions by 30 to 70% compared with continuously flooded rice systems (Singh et al., 2019).

Despite these advantages, the wider adoption of DDSR in South Asia remains limited by several agronomic constraints. Poor and uneven crop establishment, intense weed competition, and challenges in maintaining adequate and balanced nutrient availability can substantially reduce productivity under direct-seeded conditions (Shah and Wu, 2019; Shekhawat et al., 2020; Reed et al., 2022). Among these constraints, inadequate early establishment is particularly important because it can reduce plant population, weaken crop competitiveness against weeds, and ultimately limit yield potential. Therefore, management practices that improve seed performance and early crop establishment while supporting nutrient availability may be essential for realizing the productivity and resource-saving benefits of DDSR.

Seed priming is a relatively simple and affordable pre-sowing technique that can improve germination and early crop establishment under both favorable and stressful conditions (Ntshalintshali et al., 2025; Rhaman, 2025). In this process, seeds are partially hydrated to activate the early metabolic processes associated with germination, but hydration is stopped before the radicle emerges; the seeds are then dried back to a suitable moisture level for sowing (Jatana et al., 2024). Several priming approaches have been used in rice, including hydro-priming with water, osmo-priming with compounds such as $ZnSO_4$, KCl, or PEG, biopriming with beneficial microorganisms, and hormonal priming. These treatments can promote faster and more uniform germination and produce stronger seedlings, which may improve field establishment compared with untreated seeds (Roy et al., 2013; Waqas et al., 2019). This is particularly important in DDSR, where rapid and uniform crop emergence can help the rice crop become established before weeds develop strong competitive pressure. Rahman et al. (2015) also reported that seed priming improved the uniformity of emergence, highlighting its potential value for improving crop establishment under direct-seeding conditions.

Bangladesh's floodplain soils are inherently fertile but are increasingly subjected to nutrient mining due to intensive rice cultivation and overreliance on chemical fertilizers (Ononogbo et al., 2024; Imran-Hossain-Sohag et al., 2025). Continuous use of inorganic fertilizers without organic inputs has degraded soil health, reduced organic matter content, and impaired nutrient use efficiency (Chen et al., 2024; Mia and Salam, 2024).

In recent years, organic amendments have gained increasing attention as a sustainable option for maintaining soil fertility and improving crop productivity in rice-based systems, especially in the floodplain soils of Bangladesh, where soil degradation and water scarcity are growing concerns (Salahin et al., 2021; Sarker et al., 2026). Amendments such as rice straw mulch, biochar, and vermicompost are known to improve soil structure, increase water retention, and enhance microbial activity, while also supplying essential nutrients (Oyege and Balaji Bhaskar, 2023;

Selvaganapathi et al., 2025). In DDSR, rice straw mulch helps conserve soil moisture by reducing evaporation and stabilizing soil temperature under water-limited conditions (Liu et al., 2026). Biochar improves soil aeration and nutrient retention due to its porous and stable nature, thereby reducing nutrient losses. Vermicompost further supports plant growth by providing readily available nutrients and beneficial microorganisms (Hoque et al., 2022; Mahatale et al., 2026).

However, most of the existing studies have focused on the individual effects of these amendments or on conventional transplanted rice systems. Their combined influence under dry direct-seeded winter rice, particularly in floodplain environments, has received limited attention. In addition, there is still a lack of understanding of how these organic inputs interact with recommended fertilizer doses (RDF) to influence crop yield, water-use efficiency, and soil health at the same time.

In Bangladesh, preliminary evidence suggests that primed seeds in organically amended soils exhibit better seedling emergence, higher tiller production, and improved yield stability compared to unprimed seeds in conventionally fertilized soils (Rahman et al., 2023). However, systematic research under floodplain ecosystems is lacking, justifying the need for the present study.

Therefore, there is a clear need to develop location-specific and integrated agronomic practices that can maximize the productivity of floodplain soils while maintaining long-term soil health. In this context, the present study was conducted to assess the combined application of seed priming methods, hydro-priming, halo-priming, and osmo-priming with organic amendments, namely rice straw mulch, biochar, and vermicompost, under DDSR conditions in Bangladesh. The study focused on key performance indicators, including crop growth, yield formation, irrigation water use, and post-harvest soil properties. The novelty of this work lies in its integrated approach, where seed priming and organic amendments are evaluated together within a single production system. While earlier studies have mostly addressed these practices independently, their interaction under DDSR conditions in floodplain soils remains insufficiently explored. This integrated assessment provides a clearer understanding of their combined role in improving system performance and sustainability.

The objectives were to evaluate the influence of organic amendments (rice straw mulch, biochar, and vermicompost) on soil fertility, crop growth, and yield attributes; and to examine their combined effects on grain yield and overall productivity of winter rice. By integrating pre-sowing seed enhancement with soil fertility management, this study aims to identify suitable, low-cost, and sustainable options for improving soil fertility, enhancing water-use efficiency, and increasing productivity of DDSR in floodplain soils.

MATERIALS AND METHOD

Experimental site

A field experiment was conducted at the Agronomy Field Laboratory of Bangladesh Agricultural University (BAU), Mymensingh, during 2 consecutive years (2023 and 2024). The Sonatola series of the Old Brahmaputra Floodplain, which falls under the agro-ecological region of the Old Brahmaputra Floodplain (AEZ-9), contains non-calcareous dark grey floodplain soil. The experimental field was situated at 90°50’ E longitude and 24°25’ N latitude at an elevation of 18 m above sea level. The field was medium highland with well-drained silty loam soil and a pH of 6.40. Figure 1 shows the agro-climatic conditions during the research period.

Experimental treatments and design

The experimental treatment consisted of 2 factors. Factor A was priming, including no priming (P_o), hydro-priming (P_1), halo-priming with $CaCl_2$ 20,000 ppm (P_2), and osmo-priming with 50 ppm PEG 6000 (w/v) (P_3). Factor B was organic amendment, including RDF+no amendment (A_0), RDF+rice straw mulch at 7 tons ha^{-1} (A_1), RDF+biochar at 5 tons ha^{-1} (A_2), and RDF+vermicompost at 5 tons ha^{-1} (A_3). The experiment was laid out in a randomized complete block design (RCBD) with 3 replications. The total number of plots was 48. Each plot size was 2.5 m × 2.0 m.

Planting material

A high-yielding popular winter rice variety (locally called *Boro* rice), BRRI dhan88, was used as planting material in this study. This variety was developed by the Bangladesh Rice Research Institute (BRRI) from the line BRRI dhan29-SC3-28-16-10-8-HR1 (Com) and was released in 2018. Rice seeds were collected from the Agronomy Field Laboratory, BAU, Mymensingh.

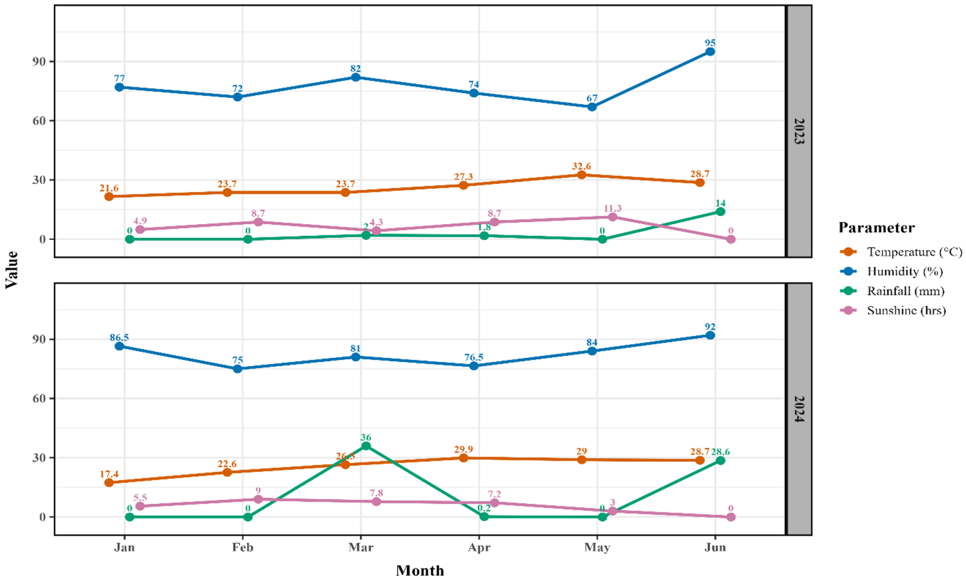

Figure 1. Distribution of monthly average air temperature, relative humidity, rainfall, and sunshine hours of the experiment site during the period from January-June 2023 and January-June 2024

Seed priming procedure

In the dry direct-seeded system, rice seeds were primed in water or in different priming agent solutions (prepared using distilled water) as per treatments for 24 hours at room temperature (25±2 °C) before sowing to enhance emergence and seedling establishment. The ratio of seed weight to solution volume was 1:5 (g ml^{-1}). Seed priming was done on February 27, 2023, and February 21, 2024. For hydro-priming, the seeds were soaked in distilled water for 24 hours. After soaking, the seeds were removed from the water and incubated for an additional 24 hours under suitable conditions to allow the seeds to initiate germination and reach the desired stage of radicle emergence before sowing.

Seed priming was carried out by soaking rice seeds in a PEG 6000 (w/v) solution (osmo-priming) or a 20,000 ppm $CaCl_2$ solution (halo-priming) for 24 hours. After priming, the seeds were removed from the solutions, air-dried back to their original moisture content, and then sown. This procedure represented seed priming rather than pre-germination, as radicle emergence was not allowed before sowing. The PEG 6000 (w/v) treatment was described using the appropriate concentration (or osmotic potential) following standard osmo-priming protocols. The seeds were then taken out of the priming agent solution, washed multiple times with distilled water to get rid of any remaining chemical residue, and then incubated until the radicle was ready to sprout.

Crop establishment and management

The experimental field was prepared under dry soil conditions using a country plow, followed by leveling with a ladder to obtain a uniform seedbed. No puddling or standing water was used during land preparation, consistent with the DDSR establishment method. After final land preparation, the field was properly leveled and laid out according to the experimental design. Each plot was cleared of weeds and stubble and cleaned. On March 2, 2023, and February 24, 2024, the sprouted seeds were sown in the main field at a rate of 4 seeds per hill at a depth of 5 cm, with row and hill distances of 25 and 15 cm, respectively.

Urea (250 kg ha^{-1}) was applied as the nitrogen (N) source, triple super phosphate (120 kg ha^{-1}) as the phosphorus (P) source, muriate of potash (149 kg ha^{-1}) as the potassium (K) source, gypsum (113 kg ha^{-1}) as the sulfur (S) source, and zinc sulphate (11.2 kg ha^{-1}) as the zinc (Zn) source. When the area had been fully prepared, all of the triple superphosphate, muriate of potash, gypsum, and zinc sulfate were applied. Three equivalent doses of urea were given at 25, 45, and 65 days after sowing (DAS). The biochar and vermicompost used in the experiment were purchased from the local agricultural input market in Mymensingh, Bangladesh.

The biochar (sawdust) used in this study exhibited a nutrient-rich composition, with an organic carbon content of 0.20% and organic matter content of 0.35%. Its nutrient profile included 1,128 ppm P, 43.5 ppm boron (B), and 0.46 meq 100 g^{-1} exchangeable K. This composition indicates that the biochar provided both carbonaceous material and essential plant nutrients, potentially contributing to improved soil fertility and nutrient availability. The vermicompost used in the study contained 1.05% organic carbon and 1.81% organic matter. Its nutrient composition included 902 ppm P, 81 ppm B, and 1.29 meq 100 g^{-1} exchangeable K. This nutrient-rich composition suggests that the vermicompost served as an important source of organic matter and essential nutrients, potentially contributing to improved soil fertility and nutrient availability for crop growth.

Intensive care was taken during the growing period for proper growth and development of the crop. Intercultural operations such as weeding, irrigation, and drainage were done during crop cultivation. Pre-emergence herbicide (Panida 33EC) was applied for weed control at 50 ml 10 l^{-1} of water, and 2 hand weedings were done at 21 and 41 DAS. Irrigation was provided only to maintain the field at a moist soil condition (75% field capacity) for successful crop growth and development. During the whole crop period, there were 11 irrigations needed for the control plot, 8 for vermicompost, 8 for biochar, and 9 for rice straw mulch in the plot used. Eventually, water was eliminated prior to the 15-day harvest period in order to optimize maturation. The crop was harvested at full maturity on June 18, 2023, and June 15, 2024, from a central 1.0 m × 1.0 m area of each plot for recording yields of grain and straw. Grains and straw were sun-dried and cleaned. Grain yields were adjusted to 14% moisture and converted to tons per hectare.

Data collection procedure

At their full maturity, the crops were harvested. When 80% of the grains turned golden yellow, the crops were considered mature. Data on various plant characters like plant height (PH), total tillers per hill (TT), effective tillers per hill (ET), non-effective tillers per hill (NET), panicle length (PL), grains per panicle (GPP), sterile spikelet per panicle (SS), 1,000-grain weight (TGW), grain yield (GY), straw yield (SY), biological yield (BY), and harvest index (HI) were recorded from randomly collected 5 hills per plot before plot harvest.

Before treatment application, soil samples were collected from a depth of 0 to 15 cm from each experimental plot using an iron core sampler to determine the initial physical and chemical properties of the soil. The soil was characterized as silty loam. The initial soil pH was 7.48, with 1.897% organic matter, 0.106% total N, 9.785 ppm available P, 0.112 meq 100 g^{-1} exchangeable K, and 7.307 ppm available S. These baseline soil properties were determined before treatment application to characterize the initial fertility status of the experimental soil and provide a basis for evaluating treatment effects during both growing seasons. After processing, the soil was taken to the Humboldt Soil Laboratory in the Department of Soil Science at BAU.

To determine field capacity (FC), collected soils with cores were soaked in water for about 48 hours. After that, the soil was allowed to air-dry for about 72 hours and then weighed. FC (%) was determined using Equation 1. Using a soil moisture meter, the field assessed the soil moisture at a depth of 15 cm every 5-day interval. When the soil moisture reached the predefined threshold that corresponded to its treatment level, irrigation was applied.

$$\text{FC (\%)} = \frac{\text{Fresh weight - Oven dry weight}}{\text{Oven dry weight}} \times 100 \quad (1)$$

Harvest index (HI)

HI is the relationship between GY and BY. HI was calculated by using Equation 2.

$$\text{HI (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100 \quad (2)$$

Statistical analysis

Data were analyzed in RStudio programming, following Linear Mixed Model (LMM), combining the 2 years' data of 2023 and 2024, considering year as a random effect using the package "lme4". Analysis of variance (ANOVA) was done with Satterthwaite's method, and multiple comparison tests were done, followed by the Tukey test. For data visualization, RStudio programming was used, and Excel was applied to arrange the dataset for analysis (R Core Team, 2022).

RESULTS AND DISCUSSION

Effect of priming on the yield and yield contributing attributes of BRRI dhan88

Seed priming significantly influenced PH (Table 1). All priming treatments resulted in higher PH than the control, with the highest value recorded under osmo-priming with PEG 6000 (w/v) (P_3), followed by hydro-priming (P_1) and halo-priming with $CaCl_2$ (P_2). The improved

Table 1. Effect of priming on the yield and yield contributing attributes of BRRI dhan88

Priming	PH (cm)	TT (no.)	ET (no.)	NET (no.)	PL (cm)	GPP (no.)	SS (no.)	TGW (g)	BY (tons ha^{-1})	HI (%)
P_0	83.60^{b}	16.60^{b}	13.20^{b}	4.27	17.40^{b}	101.00^{b}	15.70	18.30^{b}	10.50^{b}	39.10^{c}
P_1	89.90^{a}	20.80^{a}	17.10^{a}	4.32	19.90^{a}	117.00^{a}	16.00	19.80^{a}	13.00^{a}	44.10^{a}
P_2	89.70^{a}	20.10^{a}	15.50^{a}	4.36	19.90^{a}	117.00^{a}	16.20	19.20^{a}	12.40^{a}	41.50^{b}
P_3	90.80^{a}	20.60^{a}	15.50^{a}	4.78	19.80^{a}	120.00^{a}	16.00	19.30^{a}	12.70^{a}	42.60^{ab}
Level of Sig.	**	**	**	NS	**	**	NS	**	**	**
CV (%)	8.35	17.97	22.05	20.14	9.79	10.59	18.29	5.76	14.16	8.39

Note: ** = significant at 1% level of probability, NS = not significant. P_0 = no priming, P_1 = hydro-priming, P_2 = halo-priming with $CaCl_2$, P_3 = osmo-priming with PEG. PH = plant height, TT = total tillers per hill, ET = effective tillers per hill, NET = non-effective tillers per hill, PL = panicle length, GPP = grains per panicle, SS = sterile spikelet per panicle, TGW = 1,000-grain weight, BY = biological yield, HI = harvest index

plant growth observed under priming treatments could be attributed to better crop establishment and early seedling performance. Similar improvements in rice growth following seed priming have been reported by Farooq et al. (2019).

Seed priming also significantly affected TT and ET (Table 1). P_1 produced the highest TT and ET, whereas the control treatment showed the lowest values. P_3 and P_2 also improved these traits compared with the untreated control. The greater tiller development under primed treatments may reflect improved early growth conditions, which subsequently supported vegetative development. Similar results were reported by Hasan et al. (2016) and Nawaz et al. (2016), who observed increased tiller production and fertile tillers in primed rice. However, NET was not significantly influenced by priming treatments (Table 1), indicating that seed priming had little effect on the formation of non-effective tillers.

Priming treatments significantly improved PL and GPP (Table 1). P_1 and P_2 recorded the longest panicles, while P_3 also showed a comparable response. Similarly, GPP was highest under P_3, followed by P_1 and P_2, whereas the P_0 treatment showed the lowest values. These improvements suggest that seed priming positively affected reproductive development. Similar enhancement of PL following seed priming was reported by Adhikary et al. (2022). Seed priming did not significantly affect SS (Table 1), suggesting that priming treatments had limited influence on sterility under the present experimental conditions. In contrast, TGW was significantly improved by priming treatments, with P_1 recording the highest value, followed by P_3 and P_2. The improvement in grain weight may be related to better crop establishment and grain development in primed plants, as also reported by Ntshalintshali et al. (2025).

Seed priming significantly influenced GY, SY, and BY (Figure 2a, Figure 2b, and Table 1). P_1 produced the highest GY, followed by P_3 and P_2, whereas the P_0 treatment recorded the lowest yield. Similar trends were observed for SY and BY, where all priming treatments improved biomass production compared with the control. The yield improvement under priming treatments may be linked with enhanced crop establishment and improved plant growth. These findings agree with previous studies showing that seed priming can increase rice yield and biomass production (Nawaz et al., 2013; El-Serafy et al., 2021; Sen et al., 2021; Yadav et al., 2023).

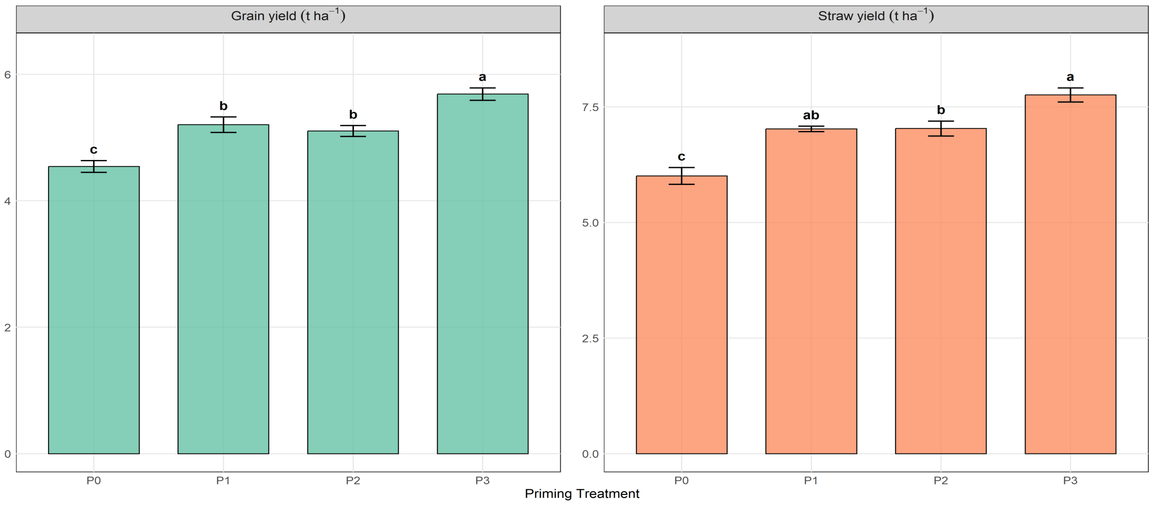

Figure 2. Effect of priming on (a) grain yield (GY, tons ha^{-1}) and (b) straw yield (SY, tons ha^{-1}) of BRRI dhan88

Note: P_0 = no priming, P_1 = hydro-priming, P_2 = halo-priming with $CaCl_2$, P_3 = osmo-priming with PEG

HI was significantly affected by seed priming (Table 1). P_1 showed the highest HI, followed by P_3 and P_2, while the control treatment recorded the lowest value. The higher HI under priming treatments indicates improved grain production efficiency. Similar effects of seed priming on HI and yield performance have been reported by Mehata et al. (2023).

Effect of organic amendment on the yield and yield contributing attributes of BRRI dhan88

The pH of BRRI dhan88 was significantly influenced by organic amendment application (Table 2). The highest PH was recorded in A_3 (92.20 cm), which was significantly higher than A_2 (88.10 cm) and A_0 (82.90 cm). A_1 (90.90 cm) also produced taller plants compared with the control. The improvement in PH under organic amendments may be associated with improved soil conditions and sustained nutrient supply during crop growth. Vermicompost can contribute to gradual nutrient release and improvement of soil organic matter, which may support plant growth and development (Haque et al., 2024). However, physiological processes related to these responses were not directly measured in this study.

TT showed significant variation among organic amendment treatments. The highest TT was recorded in A_3 (21.40), followed by A_1 (19.90) and A_2 (19.70), whereas the lowest TT was observed in A_0 (17.00). The higher TT under organic amendments indicates improved crop establishment and vegetative development. The availability of organic nutrients and improved soil physical conditions may have supported better tiller initiation and growth. Similar effects of vermicompost application on tillering improvement have been reported by Ghadimi et al. (2021).

ET was also significantly affected by organic amendments. The maximum ET was recorded in A_3 (17.20), followed by A_2 (15.80) and A_1 (15.70), while the lowest ET was observed in A_0 (12.60). The increased ET under A_3 suggests that vermicompost application supported better development and survival of productive tillers. Similar findings were reported by Rahman et al. (2023), who observed improved ET in direct-seeded rice with vermicompost application combined with chemical fertilizers. The effect of organic amendments on NET was statistically non-significant, with values ranging from 4.19 in A_1 to 4.65 in A_2 (Table 2). This indicates that organic amendments mainly influenced productive tiller development rather than altering the formation of non-productive tillers.

PL was significantly influenced by organic amendments (Table 2). The longest PL was recorded in A_3 (20.10 cm), followed by A_1 (19.40 cm) and A_2 (19.30 cm), whereas the shortest PL was observed in A_0 (18.30 cm). The improvement in PL under organic amendments may be related to better crop growth conditions and nutrient availability during reproductive development. Vermicompost, compost, and rice straw mulch may influence plant performance through different pathways, including gradual nutrient release, improved soil organic matter, and moisture conservation. These findings agree with previous reports on the positive effects of organic amendments on rice PL (Hegab, 2024).

Table 2. Effect of organic amendment on the yield and yield-contributing attributes of BRRI dhan88

Organic amendment	PH (cm)	TT (no.)	ET (no.)	NET (no.)	PL (cm)	GPP (no.)	SS (no.)	TGW (g)	BY (tons ha^{-1})	HI (%)
A_0	82.90^{c}	17.00^{b}	12.60^{b}	4.51	18.30^{b}	106.00^{c}	17.10^{a}	18.60^{b}	10.60^{c}	42.40
A_1	90.90^{ab}	19.90^{a}	15.70^{a}	4.19	19.40^{a}	113.00^{b}	15.90^{ab}	19.20^{ab}	12.40^{b}	41.40
A_2	88.10^{b}	19.70^{a}	15.80^{a}	4.65	19.30^{a}	115.00^{b}	16.30^{ab}	19.10^{ab}	12.20^{b}	41.60
A_3	92.20^{a}	21.40^{a}	17.20^{a}	4.38	20.10^{a}	122.00^{a}	14.60^{b}	19.80^{a}	13.30^{a}	41.80
Level of Sig.	**	**	**	NS	**	**	**	**	**	NS
CV (%)	8.35	17.97	22.05	20.14	9.79	10.59	18.29	5.76	14.16	8.39

Note: ** = significant at the 1% probability level ($p < 0.01$); NS = Not significant ($p \geq 0.05$). A_0 = RDF+no amendment, A_1 = RDF+rice straw mulch at 7 tons ha^{-1}, A_2 = RDF+biochar at 5 tons ha^{-1}, A_3 = RDF+vermicompost at 5 tons ha^{-1}. PH = plant height, TT = total tillers per hill, ET = effective tillers per hill, NET = non-effective tillers per hill, PL = panicle length, GPP = grains per panicle, SS = sterile spikelet per panicle, TGW = 1,000-grain weight, BY = biological yield, HI = harvest index

GPP differed significantly among treatments. The highest GPP was recorded in A_3 (122.00), representing a 15.1% increase compared with the control (106.00). This was followed by A_2 (115.00) and A_1 (113.00), whereas the lowest GPP was observed in A_0 (Table 2). The improved GPP under A_3 indicates better panicle development and grain formation. Organic amendments may contribute to reproductive growth by improving nutrient supply and maintaining favorable soil conditions. Similarly, SS were reduced by organic amendment application. The lowest SS was recorded in A_3 (14.60), followed by A_1 (15.90) and A_2 (16.30), while the highest SS occurred in A_0 (17.10). The lower SS and higher GPP under A_3 suggest improved reproductive efficiency under vermicompost application. Similar observations were reported by Bejbaruah et al. (2013).

TGW was significantly influenced by organic amendments (Table 2). The highest TGW was recorded in A_3 (19.80 g), followed by A_1 (19.20 g) and A_2 (19.10 g), whereas the lowest TGW was observed in A_0 (18.60 g). The increased TGW under organic amendments indicates improved grain filling, possibly because of better crop growth and resource availability during grain development. Vermicompost and other organic inputs may support grain filling by improving nutrient availability and maintaining soil conditions favorable for reproductive development (Meena et al., 2016; Kashif et al., 2023).

GY was significantly influenced by organic amendments (Figure 3a). The highest GY was recorded in A_3 (5.60 tons ha^{-1}), followed by A_1 (5.15 tons ha^{-1}) and A_2 (5.08 tons ha^{-1}), whereas the lowest GY was observed in A_0 (4.50 tons ha^{-1}). The higher GY under A_3 was associated with improved ET, PL, GPP, and TGW. Vermicompost, rice straw mulch, and biochar may affect crop productivity through different mechanisms; vermicompost mainly contributes to organic nutrient supply and biological activity, rice straw mulch supports moisture conservation, and biochar can improve nutrient retention. These complementary effects may contribute to improved yield performance. Similar results were reported by Rahman et al. (2023).

SY also showed significant differences among treatments. The highest SY was observed in A_3 (7.74 tons ha^{-1}), followed by A_1 (7.25 tons ha^{-1}) and A_2 (7.13 tons ha^{-1}), whereas the lowest SY occurred in A_0 (6.10 tons ha^{-1}) (Figure 3b). BY followed a similar trend, with the highest

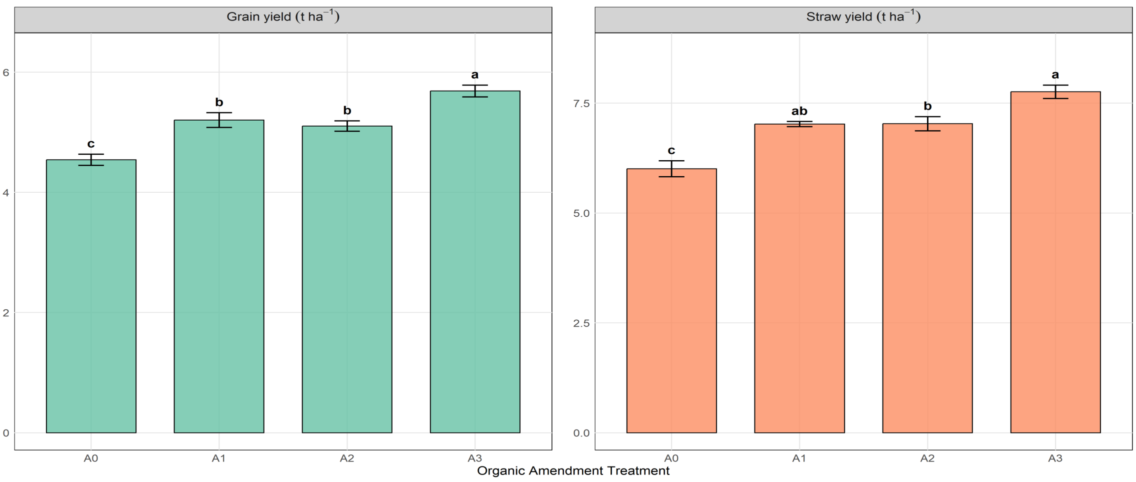

Figure 3. Effect of organic amendment on (a) grain yield (GY, tons ha^{-1}) and (b) straw yield (SY, tons ha^{-1}) of BRRI dhan88

Note: A_0 = RDF+no amendment, A_1 = RDF+rice straw mulch at 7 tons ha^{-1}, A_2 = RDF+biochar at 5 tons ha^{-1}, A_3 = RDF+vermicompost at 5 tons ha^{-1}

BY recorded in A_3 (13.30 tons ha^{-1}), representing a 25.5% increase compared with A_0 (10.60 tons ha^{-1}) (Table 2). The improved biomass production under organic amendments was mainly associated with greater GY and SY. Organic amendments can contribute to biomass accumulation by improving soil nutrient availability and supporting crop growth conditions (Iqbal et al., 2024). The effect of organic amendments on HI was statistically non-significant, ranging from 41.40 to 42.40% (Table 2). This indicates that although organic amendments increased grain and SY, the proportion of assimilates allocated to grain remained relatively consistent among treatments.

Interaction effect of priming and organic amendment on the yield contributing attributes of BRRI dhan88

PH was significantly influenced by the interaction between seed priming and organic amendments. The highest PH was recorded in P_3A_1 (93.80 cm), which was statistically similar to P_1A_3 (93.50 cm) under hydro-priming × RDF+vermicompost at 5 tons ha^{-1} (Table 3). Hydro-priming alone (P_1A_0) and other treatment combinations showed intermediate PH values ranging from 83.90 to 92.20 cm. The lowest PH was observed in P_0A_0 (72.70 cm). The improved PH under priming and amendment treatments may be associated with better crop establishment and early growth conditions. Hydro-priming facilitates rapid metabolic activation during germination, while vermicompost can contribute to gradual nutrient release and improve soil conditions through its organic matter content and biologically active compounds (Beedi et al., 2018). However, the physiological mechanisms were not directly measured in this study.

TT differed significantly among treatments. The highest TT was recorded in P_1A_3 (24.0), followed by P_1A_1 and P_2A_1 (21.30 to 21.50), whereas the lowest TT was found in P_0A_0 (14.30) (Table 3). The higher TT under P_1A_3 suggests that hydro-priming combined with vermicompost supported early establishment and vegetative development, resulting in greater tiller formation. Seed priming enhances early seedling growth by improving germination uniformity and metabolic activity, while organic amendments provide a more favorable soil environment for sustained plant development (Haque et al., 2021).

ET was significantly affected by treatment combinations, with the highest value recorded in P_1A_3 (19.80), followed by P_1A_2 (18.90) and P_3A_3 (17.40). The lowest ET occurred in P_0A_0 (10.30). The increased ET in P_1A_3 indicates improved tiller survival and reproductive tiller development under combined management. The contribution of hydro-priming to early vigor and vermicompost to nutrient supply may have supported better transition of vegetative growth into productive tillers (Gupta et al., 2022).

NET varied significantly among treatments. The lowest NET was recorded in P_1A_3 (3.66), while higher values were observed in P_3A_0 (5.41) and P_2A_3 (5.10). Other treatments showed intermediate values ranging from 4.00 to 5.28, while P_0A_0 recorded 4.57 (Table 3). The lower NET in P_1A_3, together with higher ET, indicates more efficient conversion of total tillers into

Table 3. Interaction effect of priming and organic amendment on the yield-contributing attributes of BRRI dhan88

Priming × Organic amendment	PH (cm)	TT (no.)	ET (no.)	NET (no.)	GPP (no.)	SS (no.)	TGW (g)	GY (tons ha^{-1})	SY (tons ha^{-1})	HI (%)
P_0A_0	72.70^{d}	14.30^{e}	10.30^{f}	4.57^{abc}	92.50^{f}	16.80	18.20	3.81^{h}	5.78	39.80
P_0A_1	88.60^{abc}	16.60^{cde}	13.00^{c-f}	4.05^{abc}	99.80^{ef}	16.50	18.30	4.07^{gh}	6.25	39.50
P_0A_2	82.80^{c}	17.00^{b-e}	13.70^{c-f}	3.94^{abc}	104.00^{de}	16.20	18.40	4.17^{fgh}	6.41	39.40
P_0A_3	90.50^{abc}	18.60^{b-e}	15.60^{a-e}	4.54^{abc}	107.00^{cde}	13.10	18.30	4.27^{e-h}	7.11	37.50
P_1A_0	83.90^{bc}	16.40^{de}	12.30^{ef}	4.33^{abc}	103.10^{ef}	15.40	18.70	5.05^{b-g}	5.92	45.80
P_1A_1	90.30^{abc}	21.30^{abc}	17.30^{a-d}	4.00^{abc}	114.90^{bcd}	16.60	19.90	5.88^{ab}	7.66	43.50
P_1A_2	92.20^{ab}	21.40^{ab}	18.90^{ab}	5.28^{ab}	115.40^{bcd}	17.10	19.70	5.33^{bcd}	7.35	42.10
P_1A_3	93.50^{a}	24.00^{a}	19.80^{a}	3.66^{c}	136.00^{a}	15.10	21.00	6.67^{a}	8.20	44.90
P_2A_0	88.10^{abc}	17.20^{b-e}	12.90^{def}	3.72^{bc}	109.50^{cde}	18.00	18.60	4.42^{d-h}	6.26	41.30
P_2A_1	91.10^{abc}	21.50^{ab}	17.10^{a-d}	4.28^{abc}	118.00^{bc}	15.50	19.40	5.25^{b-e}	7.33	41.70
P_2A_2	87.80^{abc}	20.20^{a-d}	15.90^{a-e}	4.33^{abc}	118.00^{bc}	15.40	19.10	5.13^{b-f}	7.43	41.00
P_2A_3	91.80^{ab}	21.50^{ab}	16.10^{a-e}	5.10^{abc}	123.00^{b}	15.90	19.70	5.67^{abc}	7.92	41.90
P_3A_0	86.70^{abc}	20.20^{a-d}	14.80^{b-e}	5.41^{a}	117.90^{bc}	18.20	18.80	4.73^{c-h}	6.44	42.80
P_3A_1	93.80^{a}	20.20^{a-d}	15.30^{b-e}	4.45^{abc}	117.80^{bc}	15.20	19.20	5.39^{bcd}	7.77	41.00
P_3A_2	89.50^{abc}	20.30^{a-d}	14.60^{b-f}	5.04^{abc}	123.00^{b}	16.40	19.30	5.70^{abc}	7.33	43.80
P_3A_3	93.30^{a}	21.70^{ab}	17.40^{abc}	4.22^{abc}	121.40^{b}	14.20	20.10	5.79^{ab}	7.73	42.80
LS	*	*	*	**	**	NS	NS	*	NS	NS
CV (%)	8.35	17.97	22.05	20.14	10.59	18.29	5.76	17.5	14.45	8.39

Note: * = significant at the 5% probability level ($p < 0.05$); ** = significant at the 1% probability level ($p < 0.01$); NS = not significant ($p \geq 0.05$). P_0 = no priming, P_1 = hydro-priming, P_2 = halo-priming with $CaCl_2$, P_3 = osmo-priming with PEG. A_0 = RDF+no amendment, A_1 = RDF+rice straw mulch at 7 tons ha^{-1}, A_2 = RDF+biochar at 5 tons ha^{-1}, A_3 = RDF+vermicompost at 5 tons ha^{-1}. PH = plant height, TT = total tillers per hill, ET = effective tillers per hill, NET = non-effective tillers per hill, GPP = grains per panicle, SS = sterile spikelet per panicle, TGW = 1,000-grain weight, GY = grain yield, SY = straw yield, HI = harvest index productive tillers. This suggests that treatment effects were more related to tiller productivity rather than only increasing total tiller number.

GPP was significantly influenced by seed priming × amendment interactions. The highest GPP was observed in P_1A_3 (136.0), whereas the lowest GPP was recorded in P_0A_0 (92.50) (Table 3). The higher GPP in P_1A_3 indicates improved reproductive development and grain formation. Hydro-priming may support early crop establishment, while vermicompost may contribute to nutrient availability and soil organic matter improvement, which together may favor panicle development and grain setting (Mondal and Bose, 2019).

PL showed a positive response to seed priming and organic amendment application. The greater PL observed under P_1A_3 may be associated with improved plant growth conditions and resource availability during reproductive development. Organic amendments such as vermicompost can improve soil physical properties and nutrient supply, which may support reproductive growth and panicle development (Alam et al., 2023).

The interaction effect on SS was statistically non-significant (Table 3). SS values ranged from 13.10 in P_0A_3 to 18.20 in P_3A_0, indicating that seed priming and amendments had limited influence on spikelet sterility under the present experimental conditions. Similarly, TGW was not significantly affected by treatment interactions. TGW ranged from 18.20 g in P_0A_0 to 21.00 g in P_1A_3, suggesting a numerical improvement with hydro-priming combined with vermicompost, although the differences were not statistically significant.

GY was significantly influenced by seed priming and organic amendment interactions. The highest GY was recorded in P_1A_3 (6.67 tons ha^{-1}), whereas the lowest GY occurred in P_0A_0 (3.81 tons ha^{-1}) (Table 3). The higher GY under P_1A_3 was associated with improvements in TT, ET, GPP, and overall crop performance. The combination of hydro-priming and vermicompost may have provided complementary benefits by improving early establishment and maintaining nutrient availability during crop growth. Similar improvements in rice productivity following integrated use of seed priming and organic inputs were reported by Rafi et al. (2016). However, direct measurements of nutrient uptake, photosynthetic activity, or physiological processes were not conducted in this study; therefore, these mechanisms require further investigation.

SY was not significantly affected by treatment interactions (Table 3). However, numerical variation was observed, with the highest SY recorded in P_1A_3 (8.20 tons ha^{-1}), followed by P_2A_3 (7.92 tons ha^{-1}), while the lowest value was observed in P_0A_0 (5.78 tons ha^{-1}). The interaction effect on HI was also non-significant. The highest HI was recorded in P_1A_0 (45.8%), followed by P_1A_3 (44.9%), whereas the lowest HI was observed in P_0A_3 (37.5%) (Table 3). These results indicate that treatment effects were more pronounced on biomass production and yield components than on assimilate partitioning efficiency.

Overall, hydro-priming combined with vermicompost (P_1A_3) consistently improved major growth and yield traits of BRRI dhan88. Vermicompost, compost, and rice straw mulch may influence crop performance through different pathways. Vermicompost is associated with gradual nutrient release and biologically active organic compounds, compost mainly contributes to nutrient buffering and organic matter improvement. Rice straw mulch, in contrast, can support moisture conservation and soil temperature regulation. However, these specific mechanisms were not directly evaluated in the present study and should be confirmed through future measurements of soil nutrient dynamics, microbial activity, root traits, physiological responses, and nutrient uptake efficiency. This suggests that the relative efficiency of assimilate partitioning into grains remained stable across treatments.

Principal component analysis (PCA), correlation, and heatmap analysis

PCA was performed to identify the major traits contributing to rice productivity under seed priming and organic amendment treatments in dry direct-seeded winter rice grown in floodplain soil of Bangladesh. The first 2 principal components explained 79.9% of the total variation in the dataset, with PC1 accounting for 68.0% and PC2 accounting for 11.9% of the total variance (Figure 4). The loading patterns indicated that TT, ET, PL, GY, PH, SY, GPP, TGW, and BY contributed positively and strongly to PC1, suggesting that this component mainly represented overall plant growth, yield formation, and biomass production. The close association among these traits indicates that improvements in vegetative growth, reproductive development,

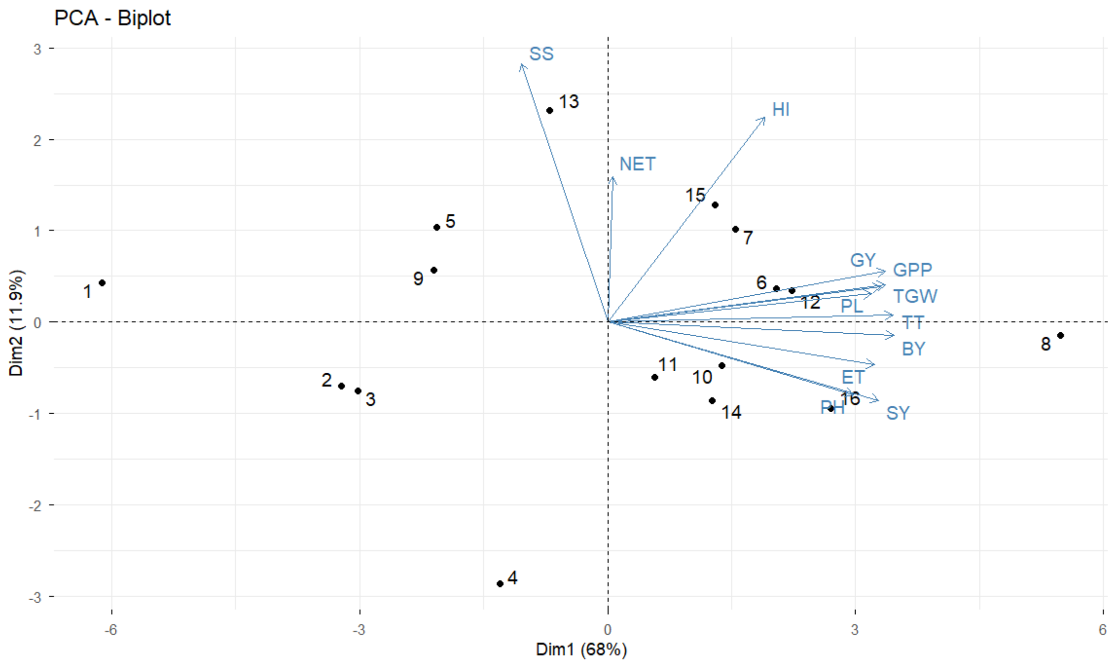

Figure 4. Biplot of PCA showing the first two principal components (PC1 and PC2)

and yield-related characteristics occurred together and were important contributors to enhanced rice productivity.

In contrast, SS and NET showed stronger associations with PC2 and displayed a negative relationship with the major PC1-related traits, indicating a distinct contribution pattern among these variables. From an agronomic perspective, this suggests that higher seedling establishment and net effective tillering may not always translate directly into increased grain yield, as excessive tiller production can increase intra-plant competition and reduce tiller productivity. The position of HI near the origin indicates that it contributed less to the variation explained by the first two components. Overall, PCA demonstrated that rice productivity under seed priming and organic amendments was primarily associated with the combined improvement of growth attributes, yield components, and biomass accumulation rather than the influence of a single trait.

Correlation analysis was performed to understand the relationships among growth, yield components, and productivity traits of DDSR under seed priming and organic amendment treatments in the floodplain soil of Bangladesh (Figure 5). The results showed that most traits were positively associated, indicating that improvements in one component contributed to overall productivity enhancement. PH showed a strong positive correlation ($p < 0.001$) with TT, ET, PL, GPP, SY, and BY, suggesting that improved plant growth supported reproductive development and biomass accumulation.

Similarly, TT, ET, and PL showed strong positive relationships with GY, SY, BY, TGW, and GPP, indicating their important roles in yield formation. The strong association of GPP and TGW with GY highlights the combined contribution of grain number and grain-filling capacity to yield improvement. The positive relationship between BY and HI suggests that greater biomass production was effectively converted into economic yield. Overall, the correlation pattern indicates that seed priming and organic amendments enhanced rice productivity through the coordinated improvement of growth, yield components, and biomass accumulation rather than through changes in a single trait.

The heat map analysis was performed to visualize the relationships between vegetative and yield-related traits and to identify the treatments contributing most strongly to rice productivity under dry direct-seeded winter rice cultivation in floodplain soils of Bangladesh (Figure 6). The evaluated traits, including TT, ET, PL, TGW, HI, GPP, SY, PH, GY, and BY, showed strong positive associations with P_1A_3. This pattern was consistent with the PCA loading and correlation analysis, indicating that these traits were the major contributors to treatment variation and were closely linked with improved rice productivity.

The strong association of P_1A_3 with TT, ET, PL, TGW, HI, GPP, SY, PH, GY, and BY suggests that the combined application of seed

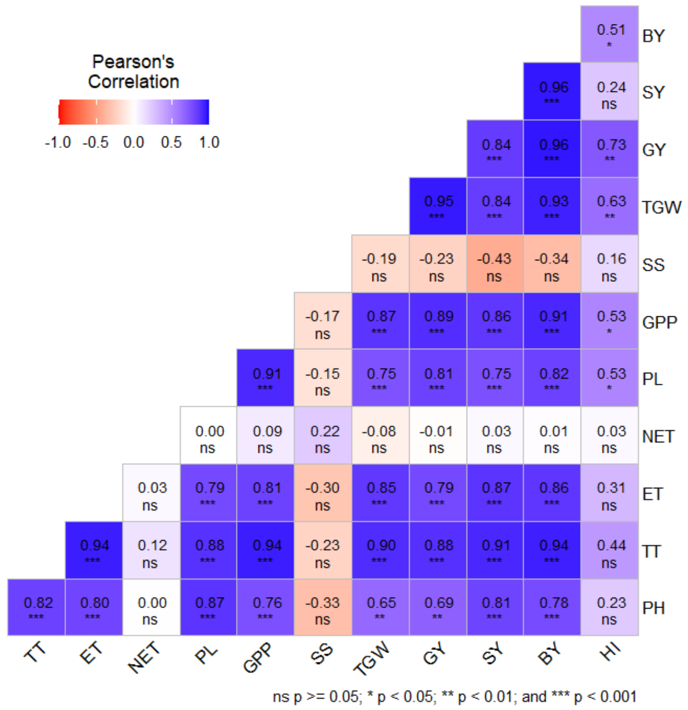

Figure 5. Pearson correlation analysis of rice productivity of dry direct-seeded winter rice in floodplain soil in Bangladesh under seed priming and organic amendments

Note: ∗∗∗, ∗∗, ∗ and NS (not significant) represent probability of ≤ 0.001, ≤ 0.01, ≤ 0.05, and > 0.05, respectively

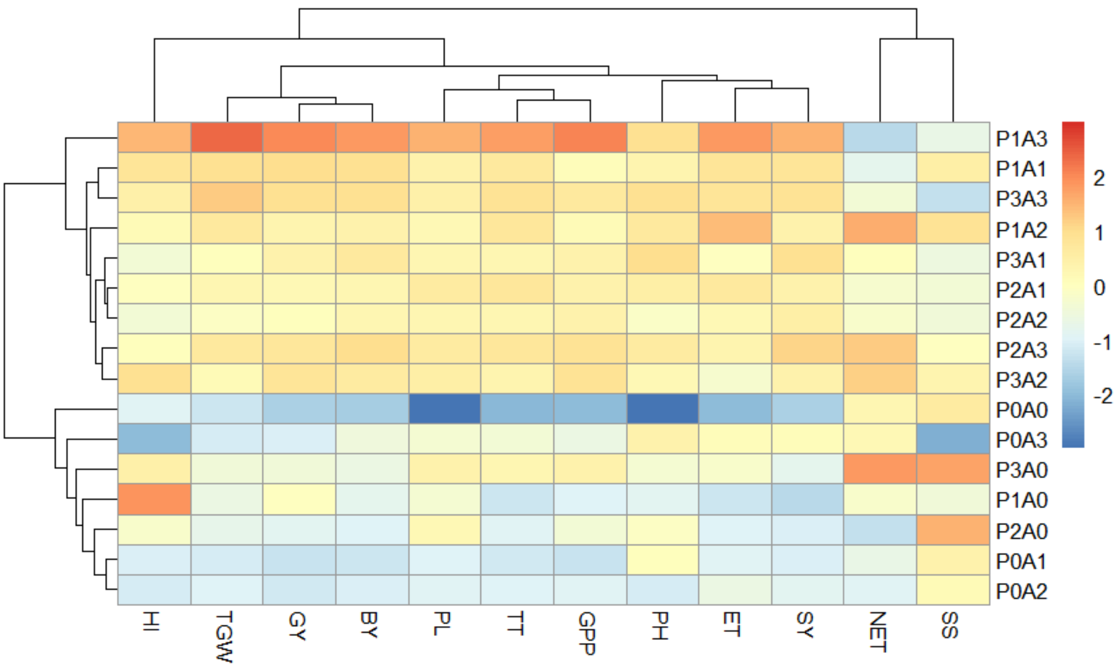

Figure 6. Heat map analysis of the impact of seed priming and organic amendments on rice productivity of dry direct-seeded winter rice in floodplain soil in Bangladesh

Note: Other details are the same as shown in Figures 2 and 3

priming and organic amendment enhanced crop establishment, growth performance, biomass production, and yield formation. In contrast, P_0A_0 showed the weakest association with these traits, reflecting lower crop performance under untreated conditions. The other treatments exhibited light to moderate or neutral relationships with the measured parameters, indicating varying levels of improvement. Overall, the heat map findings support the PCA and correlation results by demonstrating that the higher productivity of P_1A_3 was mainly associated with improved performance of key agronomic traits.

Water saving

The results presented in Table 4 show that the use of organic amendments reduced irrigation requirements compared with the control treatment. The control plots received 11 irrigations, with a total water application of 528 mm. In comparison, rice straw mulch reduced the number of irrigations to 9, resulting in a total water application of 432 mm and an 18% saving in irrigation water. Biochar and vermicompost performed better, requiring only 8 irrigations and 384 mm of water, which represented a 27% reduction compared with the control.

The lower irrigation requirement observed with the organic amendments may be related to their influence on soil–plant water relations. Rice straw mulch can cover the soil surface and reduce its direct exposure, which may help limit water loss from the soil surface. Biochar and vermicompost may also influence the availability and retention of soil water through their effects on soil conditions. However, the present study did not directly measure soil moisture dynamics, bulk density, infiltration rate, water-holding capacity, evapotranspiration, or soil porosity. Therefore, the mechanisms responsible for the observed reduction in irrigation water use cannot be confirmed directly from the present data. The proposed explanations should consequently be interpreted as possible mechanisms rather than as demonstrated effects. Further studies that directly measure soil physical and hydrological properties are needed to better understand how different organic amendments influence soil moisture availability and crop water use under DDSR conditions.

The assessment of irrigation water saving in this study was limited to the organic amendment treatments. Thus, the observed reduction in irrigation water use (18 to 27%) reflects the effect of organic amendments, while the independent contribution of seed priming to irrigation requirements or water-use efficiency was not evaluated. Consequently, no conclusion can be drawn regarding the role of seed priming in water saving based on the present results. Future studies should examine the individual and combined effects of seed priming and organic amendments on irrigation water use, soil moisture conservation, and crop water-use efficiency. Similar improvements in water-use efficiency under integrated management practices have also been reported by Mallareddy et al. (2023) and Birla and Pandey (2024). Overall, the present findings indicate that organic amendments are potential to reduce irrigation requirements and may contribute to more efficient water management under DDSR conditions, particularly in areas where water availability is limited.

Soil physical and chemical properties

Post-harvest soil analysis revealed notable improvements in soil chemical properties following the application of organic amendments (Table 5). Compared with the initial soil condition, the application of organic amendments improved several soil chemical properties. Soil organic matter increased in all amendment treatments, with the highest content recorded under rice straw mulch (2.68%), followed by vermicompost (2.61%). Biochar also increased soil organic matter to 2.25%, compared with 1.89% in the initial soil. A slight increase in soil N was also observed, reaching 0.13% under both rice straw mulch and vermicompost, compared

Table 4. Total amount of water saved (%) as affected by organic amendment

Organic amendment	No. of irrigation	Total amount of irrigated water (mm)	Water saving (%)
Control	11	528	
Rice straw mulch	9	432	18
Biochar	8	384	27
Vermicompost	8	384	27

Table 5. Post-harvest soil characteristics affected by organic amendment

Organic amendment	Organic matter (%)	N (%)	P (%)	K (%)	S (ppm)	pH
Initial	1.89	0.11	9.78	0.11	7.30	7.48
Rice straw mulch	2.68	0.13	10.60	0.11	13.65	6.43
Biochar	2.25	0.12	9.66	0.09	10.00	6.68
Vermicompost	2.61	0.13	11.45	0.09	10.77	6.60

with 0.11% in the initial soil. Available P increased notably under vermicompost (11.45%), while rice straw mulch also resulted in a higher P content (10.60%). Potassium content, however, declined slightly under biochar and vermicompost compared with the initial soil. Sulfur content increased considerably following amendment application, with the highest value recorded under rice straw mulch (13.65 ppm). Soil pH also decreased moderately from 7.48 in the initial soil, moving closer to neutral conditions.

The improved soil fertility status under the amendment treatments may have contributed to better crop performance. The biochar and vermicompost treatments also resulted in the greatest reductions in irrigation water use. These results may be related to changes in soil conditions that can influence soil water availability; however, the present study did not directly measure soil physical or hydrological properties. Therefore, the specific contribution of improved soil structure or water-holding capacity to the observed water saving cannot be confirmed from the present data. The lowest yield recorded in the untreated control (P_0A_0) may be associated with its comparatively lower soil fertility and nutrient availability. Overall, the findings indicate that organic amendments can improve important aspects of soil fertility and may support more sustainable crop production. Similar improvements in soil properties and crop productivity following the application of organic amendments have been reported by Gupta et al. (2022).

CONCLUSIONS

This study demonstrated that integrating seed priming with organic nutrient management can improve the performance of dry direct-seeded winter rice (BRRI dhan88) under floodplain soil conditions in Bangladesh. Hydro-priming provided the most consistent improvement in crop establishment and yield performance, while vermicompost was the most effective organic amendment. Their combined application produced the best overall results, indicating a promising management strategy for improving DDSR productivity under water-limited conditions. These findings highlight the potential of combining simple seed enhancement with organic nutrient management to support more sustainable rice production. However, the underlying physiological, biochemical, microbial, and direct water-use mechanisms remain unresolved. Further multi-location and long-term studies across diverse soils, cultivars, and environments, together with economic evaluation, are needed to validate the broader applicability of this approach.

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DECLARATION OF GENERATIVE AI USE

Generative AI tools (https://www.grammarly.com/ & https://quillbot.com/) were used solely for grammar correction and language refinement during the preparation of this manuscript. The authors remain fully responsible for the accuracy, originality, interpretation, and final content of the manuscript.

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