



Research

Effects of Different Biofertilizer Sources on Growth and Yield Components of Spring Rice (*Oryza sativa* L.) at Baniyani, Jhapa, Nepal

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Abstract

Rice is the principal staple crop of Nepal and plays a critical role in national food security, farm income, and rural livelihoods. However, sustained productivity is increasingly constrained by declining soil fertility, excessive reliance on chemical fertilizers, escalating input costs, and environmental concerns. In the eastern Terai region, particularly Jhapa district, spring rice cultivation is expanding, yet evidence-based recommendations on sustainable nutrient management remain limited. This study evaluated the effects of different biofertilizer and inorganic nutrient sources on the growth and yield components of spring rice. A field experiment was conducted from February to June 2025 at Baniyani, Jhapa, Nepal, under the Rice Super-Zone of the Prime Minister Agriculture Modernization Project (PMAMP). Seven nutrient treatments were arranged in a Randomized Complete Block Design with three replications using the variety Hardinath-1. Growth parameters, yield attributes, and grain yield were recorded and analyzed statistically. Significant treatment effects ($p < 0.001$) were observed for all major parameters. NPK application produced the tallest plants (114.86 cm), highest panicle weight (5.85 g), maximum grains per panicle (118.66), and the highest grain yield (7.64 t ha^{-1}). Among organic amendments, mustard seed cake performed comparably, recording the highest tiller number per hill (32.61), maximum test weight (37.06 g), and a competitive grain yield (7.30 t ha^{-1}). Goat manure resulted in moderate yield improvement, whereas the unfertilized control exhibited the lowest performance across traits. Overall, while inorganic fertilization maximized yield, mustard seed cake emerged as a promising and sustainable organic alternative for enhancing productivity of spring rice in the eastern Terai of Nepal.

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Statement of Sustainability: This study supports sustainable rice production by demonstrating that biofertilizers such as mustard seed cake and goat manure can enhance yield while improving soil health and reducing reliance on chemical fertilizers. The findings promote environmentally responsible nutrient management and contribute to climate-resilient agriculture aligned with SDG 2 (Zero Hunger).

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops worldwide and serves as the primary staple food for more than half of the global population (Mehata *et al.*, 2023; Adhikari *et al.*, 2021). In South Asia, rice production is closely linked to food security, rural employment, and national economic stability (Paudel *et al.*, 2021). In Nepal, rice occupies the largest cultivated area among cereal crops and contributes substantially to the Agricultural Gross Domestic Product (AGDP). According to recent statistics from the Ministry of Agriculture and Livestock Development (MoALD, 2021), rice is cultivated on approximately 1.49 million hectares, with total production exceeding 5.9 million metric tons and an average national productivity of $4.5\text{--}5.0 \text{ t ha}^{-1}$. Despite its importance, current productivity remains below the attainable yield potential of improved varieties, particularly under spring (Chaithe) rice cultivation systems in the Terai region (Mehata *et al.*, 2023; Baral *et al.*, 2020). Spring rice cultivation plays a significant role in increasing annual rice production in Nepal, especially in eastern Terai districts such as Jhapa (Poudel *et al.*, 2021; Wang *et al.*, 2023). Unlike monsoon rice, spring rice is grown under relatively controlled irrigation conditions; however, it is frequently exposed to temperature fluctuations, nutrient imbalances, and declining soil fertility (Regmi *et al.*, 2023).



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Continuous cropping combined with intensive reliance on synthetic fertilizers has progressively reduced soil organic matter and soil biological activity in many Terai soils (Shrestha et al., 2022). Although chemical fertilizers, particularly NPK formulations, have substantially contributed to yield improvement, their prolonged and imbalanced use has raised concerns regarding soil degradation, declining nutrient-use efficiency, environmental pollution, and rising production costs (Mehata et al., 2023; Shrestha et al., 2021). Moreover, Nepal is highly dependent on imported chemical fertilizers, making rice production systems economically vulnerable. In this context, biofertilizers and organic nutrient sources have gained increasing attention as sustainable alternatives or supplements to inorganic fertilizers (Mehata et al., 2023; Karki et al., 2018; Jalal et al., 2022). Biofertilizers include beneficial microorganisms and organic amendments that enhance nutrient availability and improve soil health (Jena et al., 2020; Gupta et al., 2016). These sources such as farmyard manure (FYM), goat manure, mustard seed cake, and mycorrhizal inoculants supply nutrients through mineralization and microbially mediated processes (Shrestha et al., 2020; Giri et al., 2022).

In addition to nutrient supply, they improve soil structure, increase water-holding capacity, stimulate beneficial microbial populations, and promote root development (Ghimire et al., 2021; Devkota et al., 2019). Mycorrhizal inoculants enhance phosphorus uptake efficiency and overall nutrient acquisition, while organic amendments gradually release nitrogen, phosphorus, and potassium, thereby reducing nutrient losses (Baral et al., 2020). Several studies conducted in Nepal and similar agro-ecological regions have demonstrated positive responses to integrated nutrient management approaches. Improvements in plant height, tillering capacity, chlorophyll content, panicle development, and grain yield have been reported when biofertilizers are combined with reduced chemical fertilizer doses (Mehata et al., 2023; Ali et al., 2012; Adhikari et al., 2023). However, the magnitude of response varies depending on the type of biofertilizer, soil characteristics, climatic conditions, and crop management practices. Organic nutrient sources differ substantially in nutrient composition, mineralization rate, carbon content, and microbial interactions, which ultimately influence crop growth dynamics and yield formation (Ranabha & Amgain, 2016). Therefore, a comparative evaluation of multiple biofertilizer sources under uniform field conditions is necessary to identify efficient and economically viable nutrient management options (Adhikari et al., 2022; Mehata et al., 2023).

Rice yield is a complex quantitative trait determined by multiple growth and yield-attributing components, including plant height, tiller number, effective tillers per hill, panicle length, panicle weight, grains per panicle, and test weight (Bailey-Serres et al., 2019; Choong et al., 2021). These traits are strongly influenced by nutrient availability during both vegetative and reproductive stages. Enhanced vegetative growth increases photosynthetic capacity and biomass accumulation, which subsequently supports reproductive development and grain filling. Physiological indicators such as SPAD-measured chlorophyll content provide insights into plant nitrogen status and photosynthetic efficiency, both of which are closely associated with yield performance (Jeson et al., 2022; Li et al., 2018). Consequently, systematic assessment of growth traits, physiological parameters, yield components, and final grain yield under different biofertilizer treatments is essential for evaluating agronomic effectiveness (Siavoshi et al., 2011). Despite increasing interest in sustainable nutrient management, limited location-specific research has been conducted in Baniyani, Jhapa, to compare the performance of diverse biofertilizer sources under spring rice conditions. Given the strategic importance of the eastern Terai in national rice production and the need to enhance productivity while maintaining soil health, identifying effective and sustainable nutrient management strategies is agronomically and economically imperative (Naz et al., 2015; Noraida & Hisyamuddin, 2021).

Therefore, the present study aimed to evaluate the effects of different biofertilizer sources on growth parameters, yield-attributing traits, physiological characteristics, biomass production, and grain yield of spring rice cultivated at Baniyani, Jhapa, Nepal. It was hypothesized that nutrient-rich organic amendments, particularly mustard seed cake, would significantly enhance growth and yield performance and could serve as sustainable alternatives to conventional inorganic fertilization under eastern Terai conditions.

2. Materials and Methods

2.1. Description of Experimental Site

The field experiment was conducted from 16 February to 12 June 2025 in a farmer's field located within the Rice Super-Zone under the Prime Minister Agriculture Modernization Project (PMAMP), Project Implementation Unit (PIU), Kachankawal-6, Baniyani, Jhapa, Nepal. The experimental site is situated at approximately 26° N latitude and 87° E longitude, with an elevation of 77 meters above sea level (masl). The area falls within the subtropical agro-climatic zone of Nepal. The region experiences three distinct seasons: rainy (monsoon), winter, and hot spring. The average annual temperature of the study site is 26.79°C, and the average annual rainfall is approximately 365.85 mm. The map of the study area is presented in Figure 1, and the meteorological data recorded during the experimental period are shown in Figure 2.

2.2. Variety and Treatment Selection

The spring rice variety Hardinath-1 was selected due to its wide adaptability in the eastern Terai, resistance to major diseases such as bacterial leaf blight and blast, tolerance to common insect pests, and yield potential of 4–6 t ha⁻¹ with a maturity duration of 115–120 days. Its fine grain quality and local acceptability make it suitable for evaluating nutrient management strategies under regional conditions. The experiment comprised seven nutrient management treatments, including organic and biofertilizer

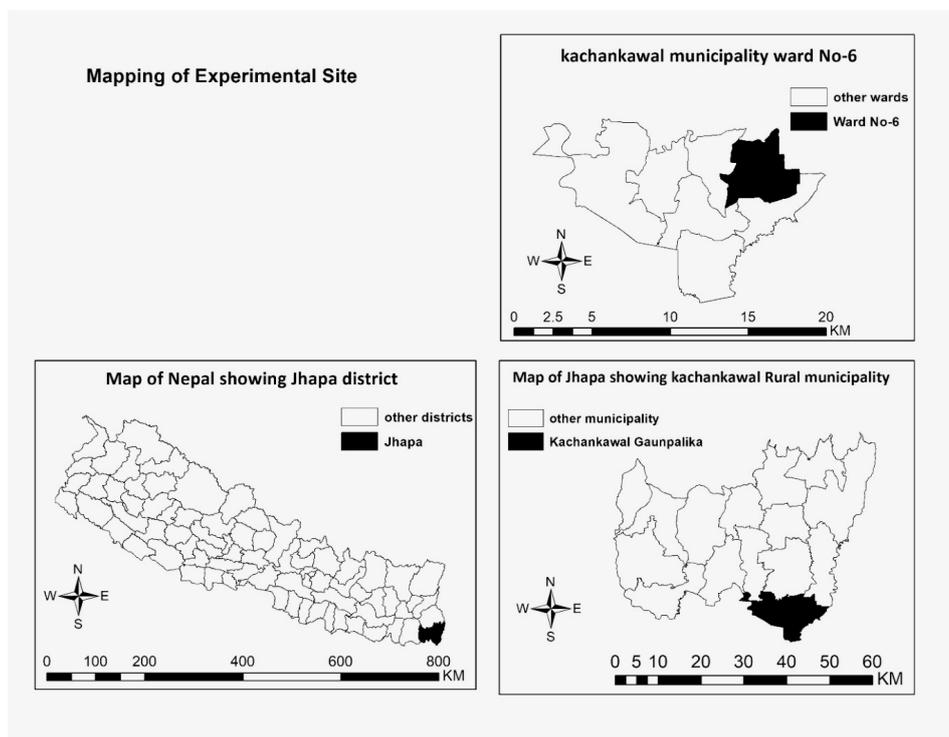


Figure 1. Location map of study area.

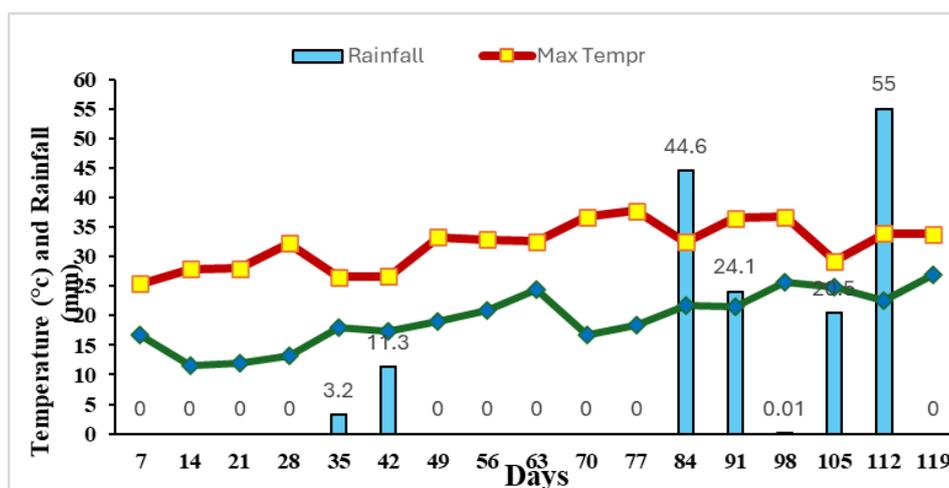


Figure 2. Meteorological data of study site.

sources, a recommended NPK dose, and an unfertilized control (Table 1). Application rates of FYM, goat manure, mustard seed cake, and mycorrhiza were determined based on their nutrient composition and regional agronomic recommendations. Average nutrient contents considered were: FYM ($\approx 0.5\text{--}0.8\%$ N), goat manure ($\approx 1.2\text{--}1.5\%$ N), and mustard seed cake ($\approx 4\text{--}5\%$ N), along with corresponding P_2O_5 and K_2O levels. Doses were calculated to supply a nutrient level comparable to the recommended nitrogen requirement of spring rice, accounting for differences in mineralization rates and nutrient release patterns. Mycorrhiza was applied at the manufacturer’s recommended rate to enhance phosphorus uptake rather than directly supply macronutrients. This nutrient-based approach ensured meaningful comparison among treatments under field conditions.

2.3. Experimental Set-up and Cultural Practices

The experiment was laid out in a Randomized Complete Block Design (RCBD) consisting of seven treatments and three replications. The treatments included five organic and biofertilizer sources, one recommended dose of NPK fertilizer, and an unfertilized control. A total of 21 experimental plots, each measuring $2\text{ m} \times 2\text{ m}$, were established. Each plot contained ten rows with ten hills per row, maintained at a spacing of $20\text{ cm} \times 20\text{ cm}$. Raised bunds were constructed around each plot to prevent lateral movement of water and nutrients, thereby ensuring treatment isolation and experimental accuracy. Seeds were pre-soaked in water for 18



Table 1. Various treatments utilized in research.

Biofertilizer sources	Applied Dose	Treatments Symbol
Control	-	T7
Mustard seed cake	4 t ha ⁻¹	T6
Mycorrhiza	20 kg ha ⁻¹	T5
FYM	15 t ha ⁻¹	T1
Organic manures Lattu	20 kg ha ⁻¹	T3
NPK	120:40:50 kg ha ⁻¹	T4
Goat manures	12 t ha ⁻¹	T2

hours and sown in a prepared nursery bed. Twenty-five-day-old seedlings were transplanted into the main field at a rate of two to three seedlings per hill. Nutrient treatments were applied to their respective plots immediately after transplanting according to the treatment schedule. Weed management was performed manually at 30 and 45 days after transplanting (DAT). Irrigation was applied uniformly across all treatments at critical growth stages, including tillering, panicle initiation, flowering, and grain filling, to avoid moisture stress and maintain uniform crop growth conditions.

2.4. Data Observation and Collection

The study evaluated the effects of different organic manure and biofertilizer sources, along with the recommended NPK dose, on the growth and yield-attributing characteristics of spring rice. For data collection, ten hills were randomly selected from the central area of each plot, excluding border rows to avoid edge effects. These hills were tagged using ribbons to ensure consistency in observations throughout the crop growth period. Data were recorded for eleven parameters at different vegetative and reproductive stages. The measured traits included plant height, total tillers per hill, effective tillers per hill, panicle length, panicle weight, grains per panicle, test weight, grain yield, straw yield, days to flowering, and days to maturity. Vegetative parameters, including plant height and total tillers per hill, were recorded at 30, 45, 60, and 75 days after transplanting (DAT), as well as at harvest. Reproductive parameters were measured at maturity and during post-harvest analysis. Plant height was measured from the soil surface to the tip of the tallest panicle. Days to flowering and days to maturity were determined through direct field observation when 50% flowering and physiological maturity were reached, respectively. Panicle length was measured as the distance from the panicle base to its tip. After harvest, 1000 grains were counted manually and weighed using an electronic balance to determine test weight. Grain yield was calculated following the procedure described by Shrestha et al. (2021), based on plot yield and adjusted to standard moisture content using a grain moisture tester, as presented in Eq. 1.

$$Grain\ yield\ (Kg/ha)_{12\%} = \frac{(100 - M) \times Plot\ yield\ (Kg) \times 10,000\ (m^2)}{(100 - 12) \times Net\ plot\ area\ (m^2)} \quad (1)$$

Here, M stands for the proportion of grain moisture content

2.5. Statistical Analysis

All recorded data were organized systematically in Microsoft Excel (2021) according to replication and treatment structure prior to statistical analysis. Analysis of variance (ANOVA) was performed using RStudio (version 4.2.3) to assess treatment effects on growth, physiological, and yield parameters, employing the agricolae, dplyr, and related statistical packages. Treatment means were compared using the Least Significant Difference (LSD) test at a 5% probability level. In addition to univariate analysis, regression and correlation analyses were conducted to determine relationships among growth traits, SPAD values, yield components, biomass, and grain yield. To comprehensively interpret treatment performance and trait interrelationships, multiple multivariate and graphical visualizations were generated, including growth trend line graphs, box plots, correlation heatmaps, treatment heatmaps, principal component analysis (PCA) with scree and biplots, hierarchical cluster dendrograms, and radar charts to illustrate multi-trait comparative performance.

3. Results

3.1. Growth Observation Parameters

3.1.1. Plant Height

The data presented in Table 2 indicate that nutrient treatments significantly affected plant height at all growth stages. At 30 DAT, plant height ranged from 50.76 cm in the control to 66.06 cm under NPK application, with NPK producing significantly taller plants. A similar trend was observed at 45, 60, and 75 DAT, as well as at harvest. At maturity, the maximum plant height (114.86 cm) was recorded under NPK, which remained statistically at par with mustard seed cake at most observation stages. Mustard seed cake consistently exhibited comparable performance to NPK, particularly at 45 and 60 DAT, highlighting its effectiveness as a nutrient-



rich organic amendment. Goat manure ranked next in performance, whereas the control treatment recorded the lowest plant height throughout the crop growth period. The pooled mean plant height was highest under NPK (98.18 cm), followed by mustard seed cake (95.40 cm), while the control recorded the lowest pooled mean (84.55 cm). The F-test revealed highly significant treatment effects ($p \leq 0.01$) at most growth stages, confirming the substantial influence of nutrient management on vegetative growth. The coefficient of variation (CV%) ranged from 9.59% to 15.61%, indicating acceptable experimental precision and reliability of the results. These trends are further illustrated in Figure 3.

Table 2. Plant height influenced by fertilizer treatments.

Treatments	Plant Height (cm)				At harvest	Pooled height
	30 DAT	45 DAT	60 DAT	75 DAT		
Control	50.76d	75.42d	95.37d	99.64e	100.51d	84.55d
Mustard seed cake	61.96ab	87.30a	104.91ab	110.20ab	112.64ab	95.40a
Mycorrhiza	55.00cd	80.94b	99.03cd	103.17cde	104.70cd	88.57bc
FYM	51.80cd	75.97cd	96.15d	101.22de	106.07c	86.03cd
Organic manures	54.80cd	79.43bc	99.24cd	104.30cd	106.23c	88.80bc
NPK	66.06a	88.50a	108.30a	113.20a	114.86a	98.18a
Goat manures	57.26bc	80.28b	101.75bc	106.81bc	108.29bc	90.88a
Grand mean	56.80	81.12	100.68	105.50	107.61	90.34
LSD	5.46	3.88	4.91	4.45	4.78	3.32
CV (%)	15.61	11.73	12.36	14.45	9.59	11.90
F-test	*	**	**	**	**	**

3.1.2. Number of Tillers per Hill

The number of tillers per hill was significantly influenced by nutrient treatments at all observation stages (Table 3; Figure 3). At 30 DAT, tiller number ranged from 15.70 in the control to 28.64 under mustard seed cake application, which produced significantly higher tillers compared to other treatments, followed by NPK and goat manure. This increasing trend persisted through 45, 60, and 75 DAT and up to harvest. At harvest, mustard seed cake recorded the highest number of tillers per hill (32.61), remaining statistically at par with NPK (30.73), whereas the control consistently produced the lowest tiller count (19.10). The pooled mean tiller number was highest under mustard seed cake (31.41), followed by NPK (29.53) and goat manure (27.86), while the control recorded the lowest pooled mean (18.22). The F-test indicated highly significant treatment effects ($p \leq 0.01$), particularly during the later growth stages, confirming the strong positive influence of nutrient sources on tiller production. The coefficient of variation (CV%) ranged from 6.38% to 8.47%, demonstrating high experimental precision and reliability.

Table 3. Tiller number per hill influenced by fertilizer treatments.

Treatments	Tiller number per hill				At harvest	Pooled tiller
	30 DAT	45 DAT	60 DAT	75 DAT		
Control	15.70d	18.13d	18.96d	19.23d	19.10d	18.22d
Mustard seed cake	28.64a	31.11a	32.08a	32.61a	32.61a	31.41a
Mycorrhiza	23.43c	26.80c	27.10bc	26.90c	26.80c	26.12c
FYM	17.56d	20.60d	21.50d	21.76d	21.83d	20.65d
Organic manures	22.70c	25.80c	26.76c	27.00c	26.76c	25.80c
NPK	26.76ab	29.23ab	30.20ab	30.73ab	30.73ab	29.53ab
Goat manures	24.68bc	27.78bc	28.71bc	29.04bc	29.08bc	27.86bc
Grand mean	22.78	25.57	26.47	26.75	26.70	25.65
LSD	3.29	3.38	3.16	3.15	2.89	3.21
CV (%)	8.47	7.99	7.56	6.89	6.38	7.92
F-test	*	*	**	**	**	**

3.2. Yield Attributing Traits

The application of different nutrient management treatments significantly influenced yield-attributing traits, physiological parameters, and final yield of spring rice (Tables 4 and 5; Figure 3). Effective tillers per hill exhibited highly significant variation ($p \leq 0.01$), with the highest number recorded under mustard seed cake (30.18), which remained statistically at par with NPK (28.30). Goat manure (26.54) and organic manure (24.40) also produced significantly higher effective tillers compared to the control (16.63),



which consistently recorded the lowest value. Days to 50% flowering showed non-significant differences among treatments; however, numerically earlier flowering was observed under NPK (55.66 days), whereas mustard seed cake (62.33 days) resulted in relatively delayed flowering. In contrast, days to 75% maturity differed significantly. Mustard seed cake required the longest duration to maturity (87.66 days), while organic manure (79.66 days), FYM (80.00 days), NPK (80.33 days), and goat manure (81.00 days) reached maturity comparatively earlier. The coefficient of variation ranged from 2.36% (days to maturity) to 13.89% (days to flowering), indicating acceptable experimental precision. Panicle weight and panicle length were significantly enhanced under nutrient-enriched treatments. NPK (5.85 g; 7.58 cm) and mustard seed cake (5.81 g; 7.51 cm) recorded the highest values and were statistically similar, whereas the control (3.35 g; 5.05 cm) exhibited the lowest performance. Grains per panicle also varied highly significantly, with NPK producing the maximum number of grains (118.66), closely followed by mustard seed cake (116.66) and goat manure (114.66), while the control recorded the minimum (93.33). Physiological and yield parameters were likewise significantly affected by fertilizer application (Table 5). Test weight ranged from 27.26 g in the control to 37.06 g under mustard seed cake, with NPK (35.60 g) and goat manure (34.30 g) remaining statistically comparable. SPAD values were highest under NPK (50.41), followed by mustard seed cake (48.21), indicating improved chlorophyll content and nitrogen status compared to the control and mycorrhiza treatments. Biomass yield was maximized under NPK (11.66 t ha⁻¹), followed closely by mustard seed cake (11.26 t ha⁻¹). Grain yield followed a similar trend, with NPK producing the highest yield (7.64 t ha⁻¹), which was statistically comparable to mustard seed cake (7.30 t ha⁻¹). Goat manure resulted in intermediate yield levels, whereas the control recorded the lowest grain yield (4.59 t ha⁻¹). The coefficient of variation ranged from 8.66% (test weight) to 14.93% (grain yield), reflecting satisfactory experimental accuracy and reliability. The graphical representation (Figure 3) corroborates these statistical findings, where NPK and mustard seed cake consistently demonstrate superior performance across effective tillers, panicle traits, SPAD values, biomass yield, grain yield, plant height, and total tillers per hill. Collectively, the results indicate that balanced inorganic fertilization and nutrient-rich organic amendments substantially enhance growth, yield components, and overall productivity compared to unfertilized and lower-performing treatments.

Table 4. Different yields attributing parameters as influenced by the application of different treatments.

Treatments	ET/H	DF	DM	PW	PL	G/P
Control	16.63e	58.66abc	83.00b	3.35e	5.05e	93.33c
Mustard seed cake	30.18a	62.33a	87.66a	5.81a	7.51a	116.66a
Mycorrhiza	24.33c	59.66ab	81.33bc	4.61c	6.31c	109.66ab
FYM	19.53d	58.00b	80.00bc	3.91d	5.61d	102.00bc
Organic manures	24.40c	59.00abc	79.66c	4.85bc	6.55bc	100.33bc
NPK	28.30ab	55.66c	80.33bc	5.85a	7.58a	118.66a
Goat manures	26.54bc	59.66ab	81.00bc	5.18b	6.88b	114.66a
Grand mean	24.27	59.00	81.85	4.80	6.50	108.04
LSD	2.78	4.44	3.48	0.47	0.49	11.74
CV (%)	6.62	13.89	2.36	5.19	3.79	5.15
F-test	***	NS	**	**	**	***

Table 5. Different yield attributing parameters as influenced by the application of different treatments.

Treatments	TW (gram)	SPAD reading	Biomass yield (t ha ⁻¹)	Grain yield (t ha ⁻¹)
Control	27.26d	32.99f	8.30d	4.59d
Mustard seed cake	37.06a	48.21b	11.26a	7.30a
Mycorrhiza	32.70bc	33.72f	8.88c	4.87cd
FYM	32.03bc	38.82d	8.93c	5.10c
Organic manures	30.20cd	36.05e	8.98c	4.95cd
NPK	35.60ab	50.41a	11.66a	7.64a
Goat manures	34.30ab	43.20c	9.53b	5.75b
Grand mean	32.88	40.48	9.64	5.74
LSD	3.39	4.29	5.39	5.19
CV (%)	8.66	12.40	12.14	14.93
F-test	**	**	**	**

Principal component analysis (PCA) was performed to elucidate the multivariate relationships among growth, physiological, and yield attributes of spring rice under different bio-fertilizer treatments. The scree plot (Figure 4a) indicated that the first principal component (PC1) explained 76.2% of the total variance, while the second principal component (PC2) accounted for 14.3%, cumu-

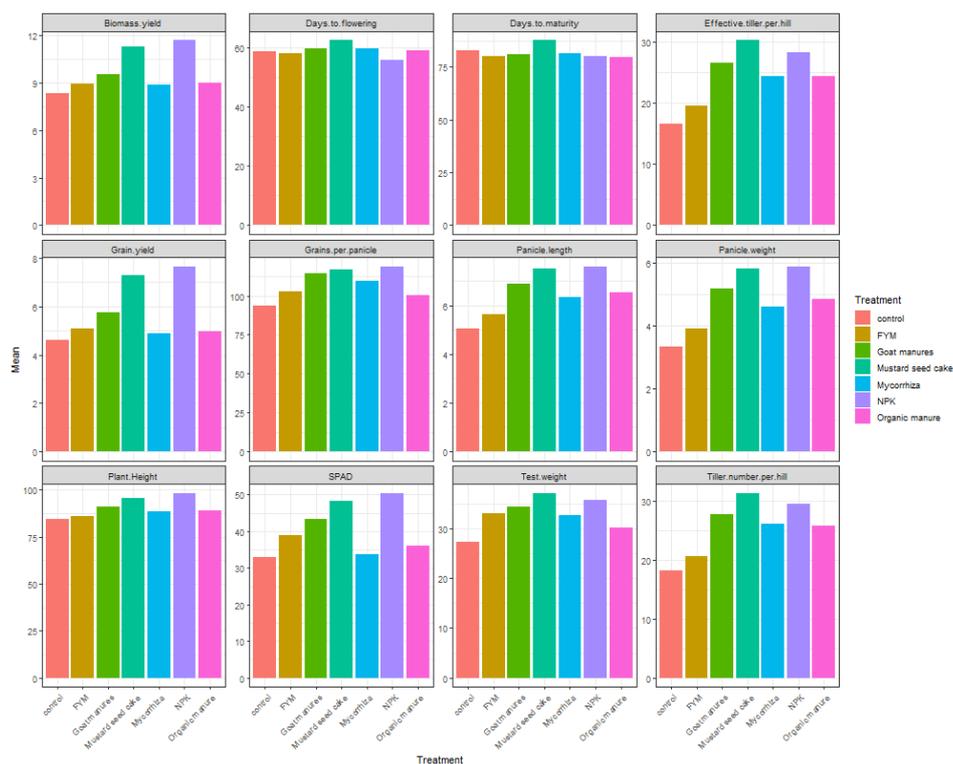


Figure 3. Bar graph showing treatment-wise effects of biofertilizers on growth and yield parameters of rice.

latively contributing 90.5% of the overall variability. The high cumulative variance explained by the first two components demonstrates that the majority of treatment-induced variation was effectively captured within a two-dimensional space, confirming the reliability of the PCA model. The PCA biplot (Figure 4b) revealed strong positive loadings of plant height, total tillers hill⁻¹, effective tillers hill⁻¹, panicle length, panicle weight, grains panicle⁻¹, test weight, SPAD value, biomass yield, and grain yield along the positive axis of PC1. The close clustering and similar vector orientation of these variables indicate strong positive correlations among vegetative growth, photosynthetic efficiency, and yield-contributing traits. Notably, the close alignment between grain yield and biomass yield vectors suggests that enhanced biomass accumulation was directly associated with improved economic yield. Treatments receiving NPK and mustard seed cake were positioned in the same quadrant as the major yield-related variables, indicating a strong positive association with superior agronomic performance. Goat manure was located closer to the origin, reflecting moderate but consistent improvements across measured traits. In contrast, the control treatment was positioned opposite to the primary yield vectors, confirming its weak association with growth and productivity parameters. Phenological traits such as days to flowering and days to maturity were oriented differently from the primary yield-associated variables, suggesting that extended crop duration was not a major determinant of yield enhancement under the present experimental conditions.

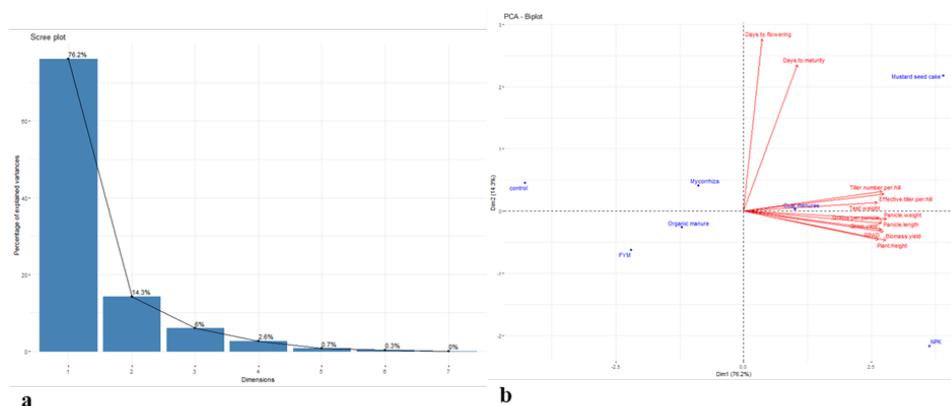


Figure 4. Principal component analysis of fertilizer treatments based on growth, physiological, and yield traits in spring rice: (a) Scree plot showing the proportion of variance explained by principal components; (b) PCA biplot illustrating the distribution of treatments and trait loadings along PC1 and PC2.



3.4. Correlation Heatmap

The correlation heatmap (Figure 5) illustrates the strength and direction of associations among growth, physiological, and yield parameters. Strong positive correlations were observed among plant height, total and effective tillers hill⁻¹, panicle length, panicle weight, grains panicle⁻¹, test weight, SPAD value, biomass yield, and grain yield. These interrelationships indicate a coordinated physiological response in which improved vegetative growth and chlorophyll content enhanced photosynthetic capacity and assimilate availability, thereby supporting reproductive development and yield formation. Grain yield exhibited particularly strong positive correlations with biomass yield, panicle weight, grains panicle⁻¹, and SPAD values, suggesting that both source strength (photosynthetic efficiency) and sink capacity (panicle traits) were critical determinants of productivity. The strong association between biomass yield and vegetative traits further confirms that enhanced canopy development contributed substantially to total dry matter accumulation and economic yield. In contrast, days to flowering and days to maturity showed weak or slightly negative correlations with yield-related variables, indicating that prolonged phenological duration was not a primary driver of yield improvement under the present experimental conditions. Overall, the correlation structure reinforces the multivariate findings and highlights nutrient-use efficiency and functional trait expression as key factors influencing yield performance.

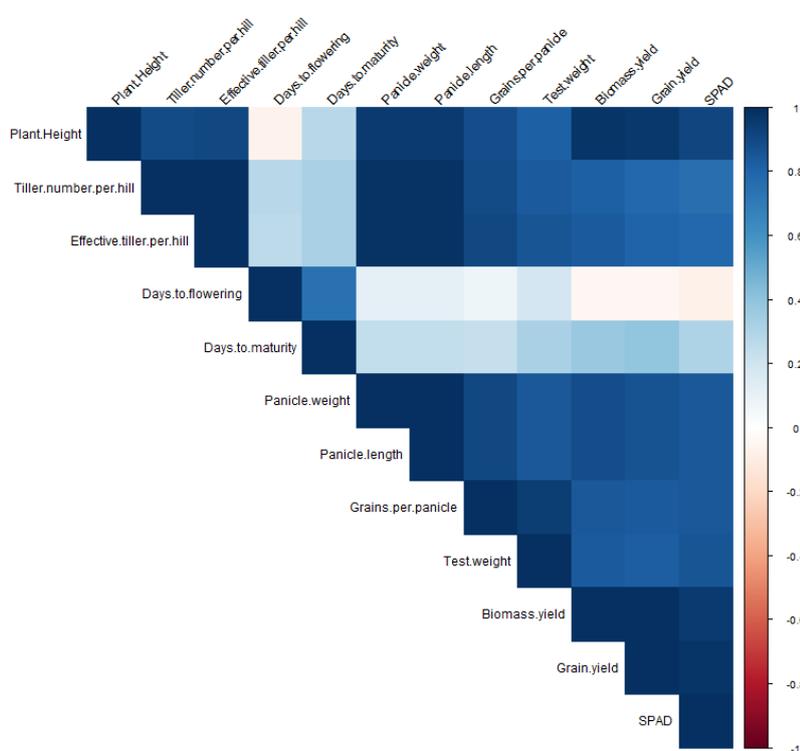


Figure 5. Correlation heatmap depicting relationships among growth, yield-attributing, physiological, and yield traits in spring rice.

3.5. Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) was performed to classify treatments based on overall similarity across growth, physiological, and yield parameters (Figure 6). The dendrogram demonstrates clear segregation of treatments into distinct clusters according to their multivariate performance profiles. Mustard seed cake and NPK clustered together at a relatively low linkage distance, indicating a high degree of similarity in their overall agronomic responses. Their close association suggests comparable effectiveness in enhancing vegetative growth, yield attributes, and final productivity. A second cluster comprised mycorrhiza and organic manure, which grouped at the lowest linkage distance within this sub-cluster, reflecting very similar performance patterns. This pair subsequently clustered with FYM, indicating moderate similarity among these organic-based treatments. Goat manure joined this group at a higher linkage distance, suggesting comparatively greater variability in its trait responses. The control treatment formed a separate branch and merged with other treatments at a relatively higher linkage distance, confirming its distinct and comparatively inferior performance across measured parameters. Overall, the dendrogram differentiates treatments into (i) high-performing inputs (mustard seed cake and NPK), (ii) intermediate organic-based amendments (mycorrhiza, organic manure, FYM, and goat manure), and (iii) the low-performing control. This clustering pattern reinforces the multivariate findings that balanced

nutrient supply whether through inorganic fertilizer or nutrient-rich organic amendments substantially improves growth and yield performance in spring rice.

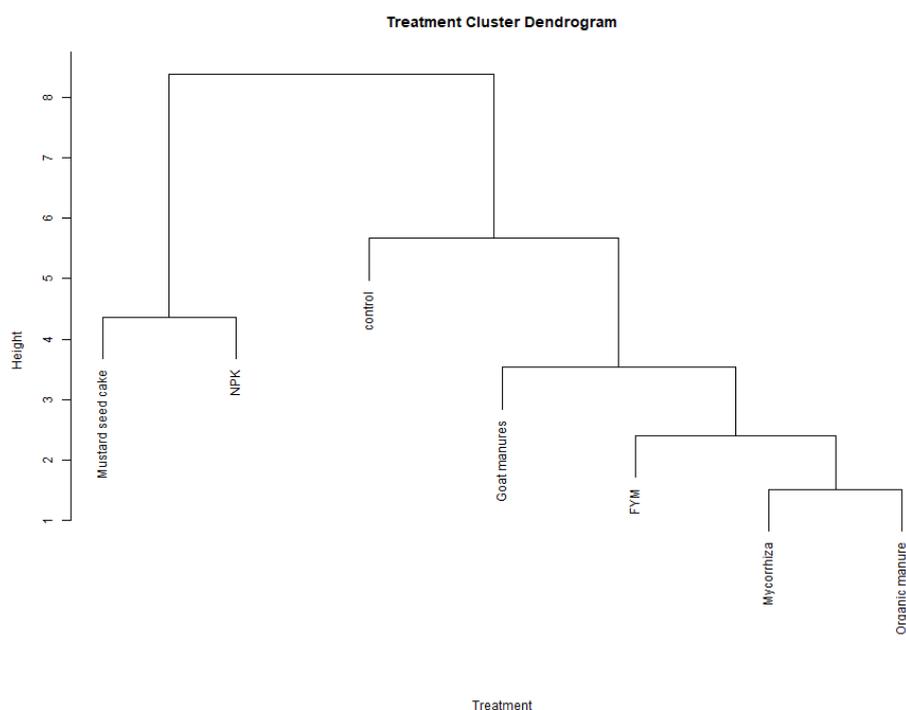


Figure 6. Hierarchical cluster dendrogram showing similarity among fertilizer treatments based on combined growth, physiological, and yield parameters.

3.6. Radar Chart

The radar chart (Figure 7) provides an integrated visualization of treatment performance across all measured growth, physiological, and yield-related traits. Treatments receiving NPK and mustard seed cake exhibit consistently broader radial expansion across most parameters, reflecting superior and balanced multi-trait performance. Their relatively uniform distribution across vegetative growth (plant height, tiller number), reproductive attributes (panicle length, grains per panicle, panicle weight), physiological status (SPAD), and yield components (biomass and grain yield) indicates comprehensive agronomic effectiveness rather than improvement in isolated traits. Goat manure demonstrates moderate radial expansion, suggesting consistent but comparatively lower trait enhancement. FYM, mycorrhiza, and organic manure display narrower and less uniform profiles, indicating partial improvements across selected parameters. The control treatment shows minimal radial coverage, confirming limited growth and yield performance. Overall, the radar analysis highlights treatment stability and functional balance, emphasizing the advantage of nutrient-rich and well-balanced fertilization strategies in optimizing multiple agronomic traits simultaneously.

3.7. Treatment Heatmap

The treatment heatmap (Figure 8) presents standardized trait values, allowing direct comparison of relative performance intensity across treatments. Higher standardized values are predominantly associated with NPK and mustard seed cake across vegetative, reproductive, physiological, and yield parameters, confirming their overall superior performance. Goat manure exhibits intermediate standardized responses, whereas FYM, mycorrhiza, and organic manure show moderate and trait-specific improvements. In contrast, the control treatment consistently displays lower standardized values, reflecting reduced growth vigor and productivity. The hierarchical clustering pattern within the heatmap corroborates the dendrogram results by grouping high-performing treatments separately from intermediate and low-performing ones. Collectively, this multivariate visualization reinforces that balanced nutrient availability significantly influences coordinated trait expression and yield enhancement in spring rice.

4. Discussion

The present study demonstrated that nutrient source significantly regulated vegetative growth, physiological status, yield-attributing traits, and final productivity of spring rice under the agro-ecological conditions of the eastern Terai. Across most parameters, NPK and mustard seed cake consistently produced superior responses, indicating that both rapid nutrient availability and sustained mineralization dynamics play critical roles in optimizing crop performance. The positive influence of balanced fertilization on plant

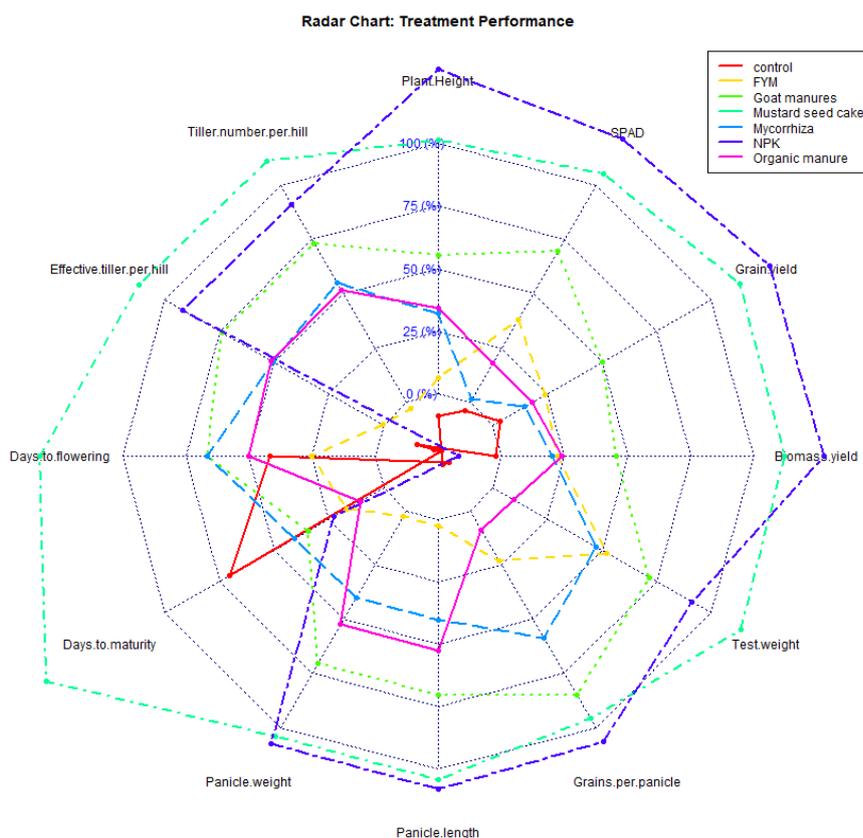


Figure 7. Radar Chart Showing Multi-trait performance of biofertilizer treatment.

height, tiller production, and biomass accumulation corroborates findings from Devkota et al. (2019), Adhikari et al. (2021), and Ghimire et al. (2021), who emphasized that adequate and synchronized nutrient supply enhances canopy development and early crop vigor in rice-based systems. Similar improvements under integrated nutrient management have also been reported by Ali et al. (2012) and Gupta et al. (2016), highlighting the importance of nutrient balance rather than nutrient source alone. The superior plant height observed under NPK can be mechanistically attributed to immediate nitrogen availability promoting chlorophyll synthesis, protein formation, and rapid cell division, while phosphorus and potassium supported root growth and metabolic regulation. Mustard seed cake exhibited comparable performance, likely due to its relatively balanced nutrient composition and gradual nutrient release through microbial decomposition. Organic amendments have been shown to enhance rhizosphere microbial activity and nutrient retention, thereby sustaining nutrient availability during critical vegetative stages (Devkota et al., 2019; Ghimire et al., 2021; Parajuli et al., 2022). Similar responses under organic inputs have been documented by Adhikari et al. (2021) and Pant et al. (2020), who reported improved vegetative growth associated with enhanced soil biological functioning and improved nutrient cycling. Mehata et al. (2023) also reported increased plant stature under both inorganic and organic nutrient sources in eastern Nepal, supporting the present findings. Tiller number and effective tillers per hill followed a comparable pattern, with mustard seed cake and NPK producing the highest values. Nitrogen availability during early growth stages is crucial for tiller initiation, while sustained nutrient supply supports tiller survival and panicle formation. Studies by Ghimire et al. (2021) and Adhikari et al. (2021) have shown that organic amendments improve soil aggregation and aeration, thereby enhancing tiller retention. Similarly, Ali et al. (2012) and Gupta et al. (2016) emphasized that balanced nutrient regimes promote uniform tiller emergence and reduce tiller mortality. Mehata et al. (2023) also reported higher effective tiller density under both NPK and mustard seed cake treatments, further validating the consistency of these responses across environments. SPAD values were highest under NPK and closely followed by mustard seed cake, indicating improved nitrogen status and chlorophyll concentration. Enhanced chlorophyll content directly improves photosynthetic efficiency and assimilate production, which ultimately supports reproductive development. Devkota et al. (2019) and Parajuli et al. (2022) reported that sustained chlorophyll activity during grain filling enhances carbohydrate translocation to developing grains. Similar findings by Pant et al. (2020) demonstrated that balanced nutrient application maintains chlorophyll stability during later growth stages, contributing to improved grain yield. Mehata et al. (2023) also observed elevated SPAD readings under recommended NPK and mustard seed cake treatments.

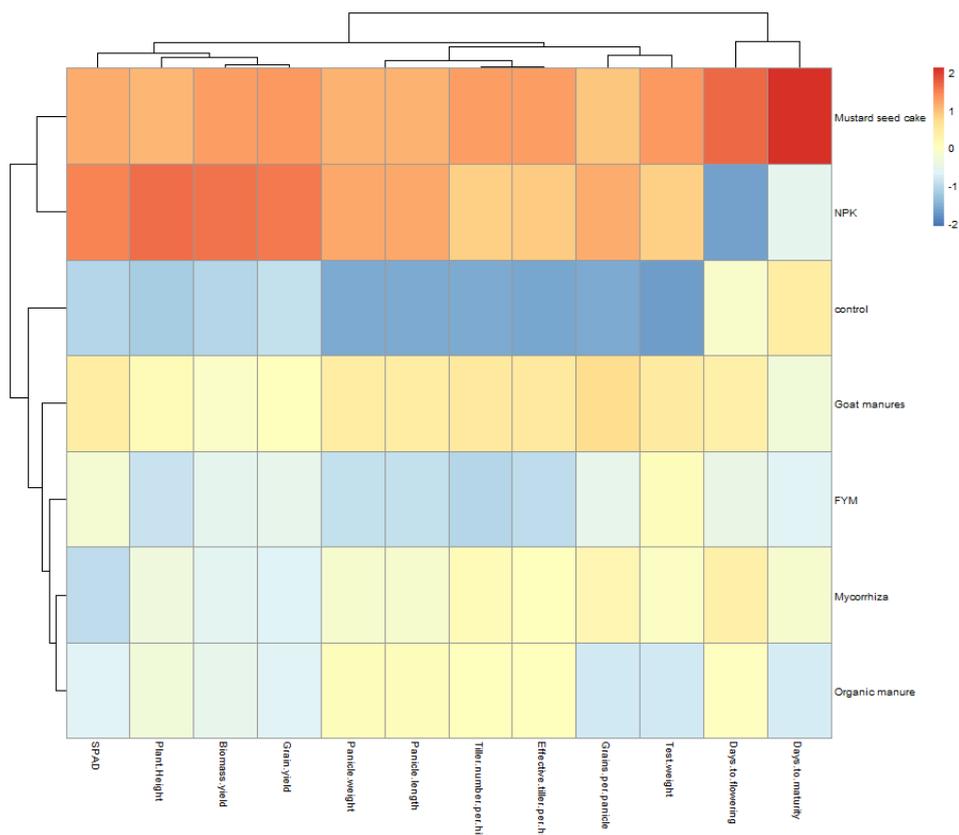


Figure 8. Heatmap showing overall performance of biofertilizer treatments on spring rice.

Reproductive traits such as panicle length, panicle weight, and grains per panicle were significantly enhanced under NPK and mustard seed cake treatments. These traits are particularly responsive to phosphorus and potassium during panicle initiation and grain filling. Gupta et al. (2016) reported that balanced fertilization enhances panicle architecture and grain number through improved assimilate partitioning and nutrient translocation. Ali et al. (2012) similarly observed that integrated nutrient management significantly improved panicle characteristics and grain number compared to sole inorganic fertilization. Mehata et al. (2023) also documented improvements in panicle traits under organic and inorganic nutrient combinations, reinforcing the present findings. Test weight was highest under mustard seed cake, followed by NPK and goat manure, suggesting enhanced grain filling under sustained nutrient availability. Grain weight is strongly influenced by the duration and efficiency of the grain-filling period, which depends on continuous assimilate supply. Pant et al. (2020) and Ghimire et al. (2021) reported that balanced nutrient regimes improve grain density by maintaining photosynthetic activity during the reproductive phase. Similar observations were made by Devkota et al. (2019), who associated higher 1000-grain weight with improved nutrient synchronization during grain filling. Mehata et al. (2023) also reported higher test weight under mustard seed cake and NPK treatments compared to control plots. Although days to 50% flowering did not vary significantly, slight delays observed under mustard seed cake may reflect prolonged vegetative growth due to gradual nitrogen release. Ali et al. (2012) and Gupta et al. (2016) noted that organic amendments can marginally extend vegetative duration without negatively affecting yield. Extended maturity under organic treatments has been associated with enhanced biomass accumulation and improved assimilate partitioning (Adhikari et al., 2021; Devkota et al., 2019). Grain yield was maximized under NPK, followed closely by mustard seed cake, significantly outperforming other treatments. The PCA and correlation analyses further confirmed the strong association of these treatments with yield-related traits, biomass accumulation, and SPAD values. Similar yield enhancement under balanced nutrient management has been widely reported (Devkota et al., 2019; Adhikari et al., 2021; Pant et al., 2020; Gupta et al., 2016). Mehata et al. (2023) also documented the superiority of NPK and mustard seed cake under eastern Terai conditions. The strong positive relationship between biomass and grain yield observed in the present study suggests efficient assimilate partitioning under nutrient-enriched treatments, a phenomenon previously highlighted by Ghimire et al. (2021) and Parajuli et al. (2022). Collectively, both univariate and multivariate analyses consistently demonstrate that nutrient availability, release dynamics, and improved soil biological conditions under NPK and mustard seed cake treatments were key drivers of enhanced growth, reproductive development, and final productivity in spring rice.



5. Conclusion

The present study demonstrates that nutrient source significantly influences vegetative growth, physiological status, yield attributes, and final productivity of spring rice under the eastern Terai conditions of Nepal. Application of recommended NPK fertilizer resulted in the highest plant height, SPAD values, panicle characteristics, biomass yield, and grain yield, underscoring the role of readily available nutrients in promoting rapid vegetative growth and enhanced reproductive development. Mustard seed cake exhibited performance comparable to NPK, particularly in improving tiller number, effective tillers, test weight, and overall yield stability. Its gradual nutrient release and beneficial effects on soil biological activity highlight its potential as a sustainable organic alternative for spring rice cultivation. Goat manure provided moderate improvements, whereas the control and FYM treatments recorded comparatively lower productivity, emphasizing the necessity of balanced and adequate nutrient supply. Multivariate analyses further confirmed the strong positive association among chlorophyll content, biomass accumulation, and grain yield under nutrient-enriched treatments. Based on the findings, recommended NPK fertilization is suitable for maximizing immediate yield, while mustard seed cake represents a promising strategy for sustaining soil health and ensuring long-term productivity in spring rice systems of the eastern Terai.

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Author Contributions

Sakshi Mandal and Amrit Karki contributed equally to the conceptualization, methodology, investigation, data curation, formal analysis, writing of the original draft, and review and editing of the manuscript. Swagat Poudel helped in conceptualization, supervision, editing, and validation. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflicts of interest: The authors report no conflict of interest in relation to the publication of this manuscript.

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Consent for publication: All authors have reviewed and approved the manuscript and consent to its publication.

Data availability: The data supporting the conclusions of this study can be obtained from the corresponding author upon reasonable request.

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