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RESEARCH

Influences of Different Transplanting Methods on Vegetative and Reproductive Traits of Spring Rice (*Oryza sativa* L.) at Belbari, Morang, Nepal

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Abstract

This study assessed the effects of five transplanting methods on the growth and yield performance of spring rice in Belbari, Morang, Nepal. Significant differences ($p < 0.01$) were observed across treatments for major vegetative and reproductive traits. The System of Rice Intensification (SRI) produced the highest plant height, tiller number, and effective tillers per hill, resulting in the greatest grain yield (7121.48 kg/ha) and biomass yield (11,037.50 kg/ha), followed by mechanical transplanting. Traditional, farmer's practice, and dry-bed methods showed comparatively lower performance. Days to 50% flowering did not differ significantly, though SRI and mechanical transplanting slightly prolonged maturity. Multivariate analyses further clarified treatment responses. PCA distinctly separated SRI and mechanical transplanting along yield-associated components, driven by strong loadings from tiller number, effective tillers, plant height, and panicle traits. The correlation matrix confirmed strong positive associations of grain yield with biomass yield, effective tillers, grains per panicle, and test weight. Radar chart patterns highlighted the holistic superiority of SRI across all measured traits, with mechanical transplanting showing moderate-to-high performance. Overall, the study demonstrates that improved transplanting methods; particularly SRI and mechanical transplanting; enhance rice productivity through stronger trait interrelationships and better resource-use efficiency. These methods offer practical solutions for addressing labor constraints and improving profitability and sustainability in Nepal's eastern Terai.

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Statement of Sustainability: This study introduces a comparative evaluation of rice transplanting methods that emphasizes labor-efficient and resource-conserving practices, offering a practical pathway toward climate-resilient rice production. By demonstrating the superior productivity and input-use efficiency of SRI and mechanical transplanting, the research supports SDGs 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 13 (Climate Action). The work is novel in its focus on method-specific performance under spring rice conditions in Nepal's eastern Terai, providing evidence-based recommendations that enhance farmers' profitability while promoting sustainable agricultural intensification.

1. Introduction

Rice (*Oryza sativa* L.), often referred to as the "king of cereals," is a staple food for over 65% of the global population (Hossain et al. 2003; Yadav and Kumar, 2011; Kumar et al., 2017). Among the cereal crops cultivated in Nepal, rice ranks first in area, production, and consumption, followed by maize and wheat (Mehata et al., 2023; Fu et al., 2012). Globally, it stands second only to wheat in area and production. In Nepal, rice contributes about 7% to the national GDP and 20% to the Agricultural GDP (AGDP). The total rice cultivation area in 2019 was 1.46 million hectares, producing 5.56 million metric tonnes with an average productivity of 3.81 t/ha. Spring rice occupies around 8% of the total rice area, while the main season rice dominates with 92% (MoAD, 2022; Ghimire et al., 2016). Minor types such as boro and bhadaiya rice occupy less than 1% of the total area. For instance, in Chitwan district, monsoon rice covers 29,700 ha

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and spring rice 4,600 ha, with a productivity of 4.4 t/ha (Poudel et al., 2020).

Despite its importance, rice production in Nepal faces challenges mainly due to the dominance of traditional manual transplanting methods. This practice involves labor-intensive operations such as puddling, nursery preparation, uprooting seedlings, and manual planting, accounting for about 15% of the total production cost (Shrestha et al., 2022). Labor scarcity during peak transplanting seasons often delays planting, adversely affecting tiller formation and yield (Kumhar et al., 2016). Since transplanting is the main establishment method in Asia (Poudel et al., 2020), rising labor costs and declining workforce availability have prompted the search for more efficient systems. Mechanical transplanting has emerged as a viable solution, reducing labor and time while improving efficiency. According to IRRI (2016), one operator can transplant 1–2 ha per day compared to only 0.07 ha manually (Jagadish et al., 2007; Jagdish et al., 2014; Javaid et al., 2012). It ensures uniform spacing, planting depth, and better crop vigor, increasing yield and profitability (Sheeja et al., 2012). Similarly, Direct Seeded Rice (DSR) offers water- and labour-saving benefits by eliminating nursery preparation and transplanting (Rahman et al., 2019). However, it faces yield limitations due to weed pressure, soil sickness, and soil-borne pathogens such as Gaeumannomyces graminis var. graminis (Jaiswal et al., 2020).

With the rapid advancement of mechanization, rice cultivation has transformed through technologies like tractor-mounted ploughs, rotary tillage, and precision planters (Poudel et al., 2020). Conservation practices such as zero-tillage and reduced tillage help maintain soil health and reduce greenhouse gas emissions (Debbarma et al., 2015), while precision planters ensure uniform seed placement and better tiller uniformity (Kumar and Jnanesha, 2017). Despite these innovations, many farmers in Belbari, Morang, still rely on conventional transplanting, which is labor-intensive and limits spring rice expansion. Hence, evaluating the effects of different transplanting methods—manual, mechanical, and direct seeding—on growth and yield parameters such as plant height, tiller number, panicle length, and grain yield is crucial.

Given the growing need for efficient, sustainable, and cost-effective rice cultivation practices in Nepal, this study was designed to evaluate the influences of different transplanting methods on the vegetative and reproductive traits of spring rice (*O. sativa*) at Belbari, Morang.

2. Materials and Methods

2.1. Description of Experimental Site

From February 2025 to June 2025, the study was conducted on a farmer's field located at Belbari-9, Morang district, in the Eastern Terai region of Koshi Province, Nepal. To precisely identify the location, the site's geographical coordinates are 26°40′6.1140″ N latitude and 87°25′49.7856″ E longitude, with an elevation of approximately 60 meters above sea level. During the study period (February–June 2025), maximum temperature ranged from approximately 30°C to 40°C, while minimum temperature increased from around 15°C to 30°C. Relative humidity was highest in June (45%) and lowest in April (30%). Precipitation peaked in March (70 mm), dropped significantly in April and May, and increased again in June, indicating the pre-monsoon build-up (**Figure 1**).

2.2. Variety and Treatment Selection

The study was conducted using the spring rice variety Hardinath-1, a widely adopted and high-yielding variety in Nepal, released by the National Agriculture Research Council (NARC). Hardinath-1 is known for its medium duration (approximately 120 days to maturity), good grain quality, and adaptability to Terai agro-climatic conditions, making it suitable for evaluating transplanting methods under eastern Terai conditions. The experiment included five different transplanting methods as treatments to assess their effects on the growth and yield performance of this variety (**Table 1**). The treatments were: Farmer's Practice, which reflects the conventional method commonly used by local farmers; Traditional Transplanting, involving older seedlings and closer spacing with manual operations; Mechanical Transplanting, which utilizes a rice transplanter for uniform spacing and reduced labor; the System of Rice Intensification (SRI), which uses younger seedlings, wider spacing, and intermittent irrigation to improve root development and plant vigor; and the Dry Bed Method, where seedlings are raised in a dry nursery before being manually transplanted. These treatments were selected to represent a range of traditional and improved transplanting techniques to determine the most effective method for optimizing the performance of Hardinath-1 in spring rice cultivation.

Figure 1. Photograph of actual rice transplanting in research field.

Table 1. Treatment details along with notations.

S. No.	Treatments	Notation
1	Farmer practices	T1
2	Traditional transplanting	T2
3	Mechanical transplanting	T3
4	SRI	T4
5	Dry bed	T5

2.3. Experimental Setup and Cultural Practices

The field experiment was conducted at Belbari, Morang, Nepal, to evaluate the influence of different transplanting methods on the growth and yield performance of spring rice. The study was laid out in a Randomized Complete Block Design (RCBD) comprising five transplanting methods as treatments with four replications, resulting in a total of 20 experimental plots. Each plot measured 3 m in length and 2 m in width, giving a total area of 6 m^2 per plot. Replications were spaced 1 meter apart, and blocks were also separated by 1 meter to minimize border effects and to facilitate uniform management practices. The treatments included Farmer's Practice, Traditional Transplanting, Mechanical Transplanting, the System of Rice Intensification (SRI), and the Dry Bed Method. In all plots, rice seedlings were transplanted using a spacing of 30 cm between rows and 20 cm between plants to ensure uniform plant distribution and optimal growth conditions. The farmer's practice reflected the locally adopted method with relatively older seedlings and closer spacing, while the traditional transplanting involved manual transplanting with less consideration for spacing and seedling age. The mechanical transplanting treatment used a rice transplanter machine, ensuring uniform seedling depth and spacing. The SRI method involved transplanting younger seedlings with wider spacing and intermittent irrigation to promote better root development and tillering. The dry bed method involved raising seedlings in a dry nursery and then manually transplanting them into the field. All agronomic practices including fertilizer application, irrigation, pest and weed management were uniformly applied across all treatments based on standard recommendations to ensure that observed differences were solely due to transplanting methods. This experimental setup was carefully designed to minimize experimental error and enhance the accuracy and reliability of the results, allowing for a robust comparison of the different transplanting methods under similar field conditions.

2.4. Data Observation and Collection

The study assessed the impact of different transplanting methods on spring rice development and yield-attributing attributes. Ten hills from the Center of each plot were randomly chosen for data collection, with the boundary hills being disregarded. Ribbons were used to tag these hills, and data was collected for 12 distinct features at various vegetative and reproductive development phases. These characteristics were plant height, effective and total tillers per hill, grain and straw yields, test weight, grains per panicle, panicle length, days to blooming, days to maturity, and panicle weight. The vegetative data including plant heights, and the total number of tillers per hill were taken at 30, 45, 60, and 75 DAT and harvest respectively. Similarly, measurements of the reproductive parameters were made before and after rice harvesting. After harvest, 1000 seeds were counted and weighed using an electric weighing machine to determine the test weight. The height of the plant was measured from the lower root to the tip of the plant. Days until blooming and days till maturity were determined directly from observation, and panicle length—the separation between the base and the tip of the panicle was computed. Grain yield was calculated using the method suggested by Shrestha et al. (2021) by assessing the grain's moisture content using a grain moisture tester and plot yield, as given 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

2.6. Statistical Analysis

The data was systematically entered in chronological order based on replication and treatment blocks using Microsoft Excel (2021). Subsequently, Analysis of Variance (ANOVA) was carried out using R-Studio statistical software (version 4.2.3) to evaluate the major agronomic traits of spring rice. The analysis was conducted utilizing the 'datasets' and 'agricolae' packages in R. To determine significant differences among treatment means, the Least Significant Difference (LSD) test was applied at the 5% level of significance ($p < 0.05$). In addition, regression analysis was performed to further examine the relationship between growth and yield parameters.

3. Results

3.1. Growth Observation Parameters

3.1.1. Plant Height

The results revealed significant differences ($p < 0.01$) in plant height among the different transplanting methods at all observation stages—30, 45, 60, 75 days after transplanting (DAT), and at harvest—as well as in the pooled mean height (**Table 2** and **Figure 1**). At 30 DAT, the highest plant height (55.56 cm) was recorded under the System of

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Rice Intensification (SRI), which was significantly superior to all other treatments. This was followed by mechanical transplanting (50.26 cm), while the shortest plant height (42.61 cm) was observed under traditional transplanting. At 45 DAT, both SRI (78.00 cm) and mechanical transplanting (75.60 cm) resulted in significantly taller plants compared to other methods. Dry bed (68.46 cm), traditional transplanting (68.97 cm), and farmer practices (69.95 cm) were statistically at par and showed lower values. At 60 DAT, SRI maintained the highest plant height (97.80 cm), followed by mechanical transplanting (93.21 cm), whereas traditional transplanting had the lowest value (87.58 cm), showing a statistically significant difference among treatments. By 75 DAT, the SRI method continued to exhibit the tallest plants (102.70 cm), followed closely by mechanical transplanting (98.50 cm). The shortest plant height (91.74 cm) was observed in traditional transplanting. At harvest, plant height remained highest in the SRI treatment (104.36 cm), significantly greater than farmer practices (97.96 cm), dry bed (99.57 cm), and traditional transplanting (93.19 cm). Mechanical transplanting also performed well (100.94 cm), statistically at par with SRI but superior to traditional methods. The pooled mean plant height over all observation stages was significantly higher in the SRI method (87.68 cm), followed by mechanical transplanting (83.70 cm), while the lowest pooled height was observed in traditional transplanting (76.81 cm). The LSD (Least Significant Difference) values at 5% level ranged from 3.06 to 4.67 across growth stages, confirming significant variation among the transplanting methods. The coefficient of variation (CV) ranged from 12.43% to 14.95%, and the F-test was highly significant ($p < 0.01$) for all stages, indicating consistent treatment effects.

Table 2. Effect of different planting methods on plant height.

Treatments	Plant Height (cm)				At harvest	Pooled height
	30 DAT	45 DAT	60 DAT	75 DAT		
Farmer practices	46.93^{bc}	69.95^{b}	91.42^{bc}	96.48^{b}	97.96^{b}	80.55^{c}
Traditional transplanting	42.61^{d}	68.97^{b}	87.58^{c}	91.74^{c}	93.19^{c}	76.81^{d}
Mechanical transplanting	50.26^{b}	75.60^{a}	93.21^{b}	98.50^{ab}	100.94^{ab}	83.70^{b}
SRI	55.56^{a}	78.00^{a}	97.80^{a}	102.70^{a}	104.36^{a}	87.68^{a}
Dry bed	44.26^{cd}	68.46^{b}	89.65^{bc}	94.71^{bc}	99.57^{b}	79.81^{d}
Grand mean	47.93	72.4	91.93	96.83	99.20	81.66
LSD	3.66	4.09	4.07	4.47	4.67	3.06
CV (%)	14.95	13.66	12.87	13.00	13.05	12.43
SEM	1.153	0.993	0.946	1.012	1.024	0.938
F-test	**	**	**	**	**	**

3.1.2. Number of Tillers per Hill

The number of tillers per hill varied significantly ($p < 0.01$) among the different transplanting methods at all growth stages (30, 45, 60, 75 DAT, and at harvest) as well as in the pooled mean (**Table 3** and **Figure 2**). At 30 DAT, the highest tiller number (26.64) was recorded in the System of Rice Intensification (SRI) method, which was significantly superior to all other treatments. This was followed by mechanical transplanting (24.34), while the lowest number of tillers was observed in traditional transplanting (20.91) and dry bed (21.06), which were statistically at par. At 45 DAT, SRI again produced the maximum tillers (29.11), followed by mechanical transplanting (27.64). Traditional transplanting (23.81), farmer practices (25.73), and dry bed (24.09) produced significantly fewer tillers per hill. At 60 DAT, the trend remained consistent, with SRI exhibiting the highest tiller number (30.08), followed by mechanical transplanting (28.64). Traditional (24.56), dry bed (24.99), and farmer practices (26.66) lagged. At 75 DAT, the SRI method showed the greatest tiller number per hill (30.61), which was significantly higher than all other treatments. Mechanical transplanting recorded 29.11 tillers per hill, while the lowest was in traditional transplanting (24.41). At harvest, SRI maintained the highest tiller count (30.61), which was statistically on par with mechanical transplanting (29.04), but significantly higher than the rest. Traditional transplanting had the lowest tiller number (24.29), followed by dry bed (25.33). In terms of pooled tiller number, SRI again topped with 29.41 tillers per hill, followed by mechanical transplanting (27.76), whereas traditional transplanting had the lowest pooled tiller number (23.60), significantly lower than all other treatments. The LSD

(Least Significant Difference) at 5% ranged from 2.73 to 3.02, confirming statistically significant differences among the transplanting methods. The CV ranged from 6.51% to 8.47%, indicating good precision in the experiment. The F-test was highly significant ($p < 0.01$) for all stages, indicating consistent treatment effects on tiller production.

3.1.3. Effective Tillers per Hill

There was a significant difference ($p < 0.05$) among the transplanting methods for the number of effective tillers per hill (**Table 3**). The highest number of effective tillers was recorded under the SRI method (26.30), which was significantly higher than traditional transplanting (21.84). Mechanical transplanting (24.76) and farmer practices (24.50) were statistically at par with each other and with SRI, while dry bed treatment (23.03) was lower than mechanical and SRI but not significantly different from farmer practices.

Table 3. Effect of different transplanting methods on number of tiller per plants.

Treatments	Tiller Number per Hill				At harvest	Pooled tiller
	30DAT	45DAT	60DAT	75DAT		
Farmer practices	22.63^{bc}	25.73^{bc}	26.66^{bc}	27.00^{bc}	27.03^{bc}	25.15^{c}
Traditional transplanting	20.91^{c}	23.81^{c}	24.56^{c}	24.41^{c}	24.29^{d}	23.60^{c}
Mechanical transplanting	24.34^{ab}	27.64^{ab}	28.64^{ab}	29.11^{ab}	29.04^{ab}	27.76^{ab}
SRI	26.64^{a}	29.11^{a}	30.08^{a}	30.61^{a}	30.61^{a}	29.41^{a}
Dry bed	21.06^{c}	24.09^{c}	24.99^{c}	25.26^{c}	25.33^{cd}	24.15^{c}
Grand mean	23.12	26.08	26.99	27.28	27.26	26.14
LSD	3.02	2.88	2.87	2.83	2.73	2.86
CV (%)	8.47	7.18	6.90	6.74	6.51	7.10
SEM	0.641	0.607	0.618	0.655	0.650	0.632
F-test	**	**	**	**	**	**

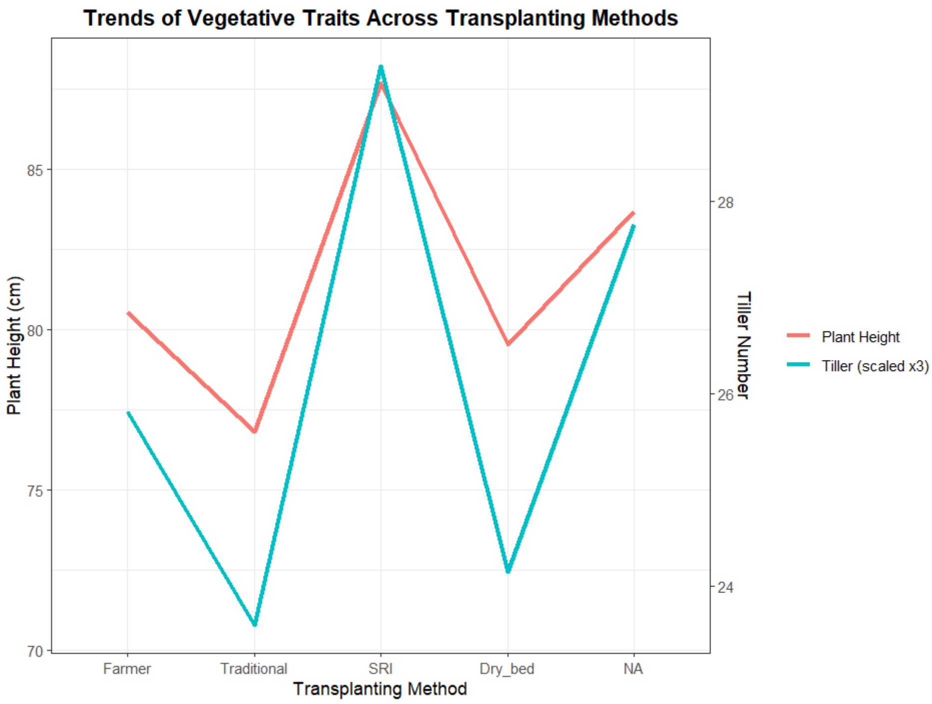

Figure 2. Growth trends of vegetative traits across transplanting methods.

3.2. Yield Attributing Traits

3.2.1. Panicle Length

Panicle length was significantly influenced ($p < 0.05$) by the transplanting method. The longest panicle was observed in mechanical transplanting (30.36 cm), significantly higher than in traditional transplanting (27.24 cm). Other treatments including SRI (28.90 cm), farmer practices (28.90 cm), and dry bed (27.83 cm) were statistically at par with one another.

3.2.2. Panicle Weight

There were no significant differences (NS) among the transplanting methods for panicle weight. All treatments produced statistically similar panicle weights, ranging from 3.31 g in traditional transplanting to 4.26 g in farmer practices. Despite numerical differences, high variability (CV = 22.31%) and overlapping standard errors contributed to non-significance.

3.2.3. Grains per Panicle

There was a significant effect ($p < 0.05$) of transplanting method on the number of grains per panicle. The highest number of grains was recorded in the SRI method (113.66), followed by mechanical transplanting (111.66), and farmer practices (109.50). The lowest number of grains per panicle was observed in the dry bed method (101.49), which was significantly lower than SRI and mechanical transplanting. Traditional transplanting produced 107.89 grains per panicle, statistically similar to other treatments except SRI.

Table 4. Effect of different transplanting methods on reproductive traits.

Treatments	ET/H	DF	DM	PW	PL	G/P
Farmer practices	24.50^{ab}	59.50^{a}	80.75^{c}	4.26^{a}	28.90^{ab}	109.50^{ab}
Traditional transplanting	21.84^{c}	59.25^{a}	81.75^{bc}	3.31^{a}	27.24^{b}	107.89^{ab}
Mechanical transplanting	24.76^{ab}	58.25^{a}	83.50^{a}	4.06^{a}	30.36^{a}	111.66^{a}
SRI	26.30^{a}	58.50^{a}	83.25^{ab}	4.13^{a}	28.90^{ab}	113.66^{a}
Dry bed	23.03^{bc}	61.50^{a}	83.50^{a}	3.66^{a}	27.83^{ab}	101.49^{b}
Grand mean	24.08	59.4	82.4	4.08	28.55	108.84
LSD	2.66	3.26	2.27	1.40	2.74	9.05
CV (%)	7.17	13.57	11.79	22.31	16.24	15.39
SEM	0.505	0.489	0.407	0.221	0.439	1.477
F-test	*	NS	*	NS	*	*

3.2.4. Test Weight

Test weight is a critical quality parameter reflecting the grain density and quality, which directly influences market value and consumer preference. In this study, the highest test weight was recorded under the System of Rice Intensification (SRI) method at 29.83 grams, which was significantly superior to traditional transplanting (25.24 g) and dry bed (25.99 g) methods. The enhanced test weight observed in SRI could be attributed to improved plant vigor, efficient nutrient uptake, and better grain filling resulting from optimal plant spacing and reduced transplanting shock. Mechanical transplanting (27.96 g) and farmer practices (27.13 g) produced intermediate test weights that were statistically similar, indicating that mechanization and conventional farmer methods maintain moderate grain quality. These results demonstrate that improved transplanting methods like SRI not only increase yield but also enhance grain quality, which is essential for meeting consumer and market standards.

3.2.5. Days to 50% Flowering

The transplanting methods did not show a statistically significant effect (NS) on the number of days to 50% flowering. The values ranged from 58.25 days in mechanical transplanting to 61.50 days in dry bed method. Although mechanical transplanting and SRI appeared to slightly hasten flowering, the variation was not statistically significant as indicated by the F-test.

3.2.6. Days to 75% Maturity

Significant differences ($p < 0.05$) were observed among treatments for days to 75% maturity. Mechanical transplanting and dry bed methods had the longest duration to maturity (83.50 days), statistically similar to SRI (83.25 days). In contrast, farmer practices matured earlier (80.75 days), and traditional transplanting showed intermediate maturity (81.75 days). The delayed maturity in mechanical and SRI methods may be due to more robust vegetative growth supporting prolonged grain filling.

3.2.7. Grain Yield

Grain yield is the ultimate measure of crop productivity and directly impacts food security and farmer income. The results showed that the SRI method produced the highest grain yield of 7,121.48 kg/ha, significantly outperforming traditional transplanting (5,720.20 kg/ha) and dry bed methods (6,183.28 kg/ha). This substantial yield advantage is likely due to the combined effects of better plant establishment, increased effective tillers, improved panicle characteristics, and enhanced grain filling under SRI. Mechanical transplanting (6,781.70 kg/ha) and farmer practices (6,529.18 kg/ha) yielded moderately high grain outputs, demonstrating the positive influence of mechanization and conventional farmer knowledge in improving yield compared to traditional transplanting. These findings emphasize that adoption of improved transplanting methods can significantly boost rice productivity, helping to address labor constraints and increase profitability for farmers.

3.2.8. Biomass Yield

Biomass yield reflects the total above-ground plant mass and is an important indicator of crop growth performance and overall productivity. The SRI method yielded the highest biomass production at 11,037.50 kg/ha, significantly higher than the traditional transplanting method, which produced 9,655.14 kg/ha. This increase in biomass under SRI can be linked to enhanced vegetative growth, higher tiller numbers, and improved photosynthetic efficiency associated with optimal plant spacing and better water and nutrient management. Mechanical transplanting (10,644.16 kg/ha) and farmer practices (10,216.66 kg/ha) also showed comparatively higher biomass yields than traditional transplanting and dry bed (9,917.16 kg/ha), underscoring the benefits of mechanization and improved management practices in biomass accumulation. Higher biomass is critical not only for grain yield but also for straw production, which holds economic importance in many rice-growing regions.

Table 5. Effect of different transplanting methods on test weight, biomass and Grain yield.

Treatments	TW (g)	Biomass yield (kg/ha)	Grain yield (kg/ha)
Farmer practices	27.13^{ab}	10216.66^{bc}	6529.18^{bc}
Traditional transplanting	25.24^{b}	9655.14^{d}	5720.20^{d}
Mechanical transplanting	27.96^{ab}	10644.16^{ab}	6781.70^{ab}
SRI	29.83^{a}	11037.50^{a}	7121.48^{a}
Dry bed	25.99^{b}	9917.16^{cd}	6183.28^{c}
Grand mean	27.23	10294.13	6467.17
LSD	3.72	466.31	421.24
CV (%)	8.86	12.94	14.22
SEM	0.616	128.549	123.187
F-test	*	*	*

Figures 3 and **4** provide a comparative overview of the distribution and mean performance of vegetative and yield traits across the five transplanting treatments. These visual summaries support the trait-specific findings described in the preceding sections.

3.3. Regression Analysis

The regression analyses illustrated in **Figures 5** and **6** comprehensively reveal the relationships between various agronomic traits and grain yield (kg/ha) in rice, shedding light on the key parameters influencing productivity. Strong positive correlations were observed between vegetative growth traits and yield. For instance, plant height exhibited a highly significant relationship (R^2 = 0.73, p = 1.6e−06), with the regression equation (y = −2700 + 110x) indicating that each centimetre increase in plant height could lead to a yield increase of about 110 kg/ha, underscoring the contribution of vigorous vegetative growth to grain production. Similarly, tiller number per hill also showed a significant and strong correlation (R^2 = 0.70, p = 3.9e−06), suggesting a 160 kg/ha yield boost for every additional tiller (y = 2200 + 160x), while effective tillers per hill had a slightly lower but still significant R^2 of 0.65 (p = 1.9e−05), indicating a 200 kg/ha gain per effective tiller (y = 1700 + 200x), highlighting the importance of productive tillering.

Conversely, reproductive and phenological parameters such as days to 50% flowering (R^2 = 0.043, p = 0.38) and panicle weight (R^2 = 0.043, p = 0.38) showed very weak, non-significant relationships, suggesting limited direct influence on yield. Days to 75% maturity had a slightly stronger R^2 of 0.15 (p = 0.089) and a positive trend (y = −3300 + 120x), hinting that prolonged maturity might marginally support higher yield via extended grain filling, though not conclusively. In Figure 4, panicle length showed a moderately positive and significant correlation (R^2 = 0.32, p = 0.0092), indicating a 160 kg/ha increase per centimetre of panicle length (y = 1900 + 160x), emphasizing the role of longer panicles in supporting more spikelets and grains. Grains per panicle had a weaker but suggestive correlation (R^2 = 0.19, p = 0.056), with a 36 kg/ha yield increment per additional grain (y = 2500 + 36x), though the result was marginally non-significant. Importantly, test weight exhibited a significant moderate correlation with yield (R^2 = 0.45, p = 0.0013), where each additional gram of test weight led to a 130 kg/ha yield increase (y = 2800 + 130x), underscoring the contribution of grain quality and density. The strongest yield predictor in this analysis was biomass yield (R^2 = 0.57, p = 0.00011), with the regression model (y = −1000 + 0.73x) suggesting that each kilogram of additional biomass resulted in a 0.73 kg/ha rise in grain yield, reflecting the tight coupling between vegetative growth and grain output. Together, these findings reveal that vegetative parameters such as plant height, tiller number, effective tillers, test weight, and biomass yield are the most influential contributors to grain yield, while phenological traits and certain reproductive characteristics show weaker associations. This suggests that enhancing early vegetative vigor, tillering capacity, and grain filling efficiency through optimal management and improved transplanting methods can be strategic levers for maximizing rice productivity in spring rice cultivation systems.

3.4. Insightful Multivariate Exploration of Spring Rice Traits Across Transplanting Methods

3.4.1. Principal Component Analysis

Principal Component Analysis (PCA) biplot of spring rice traits across transplanting methods displayed in **Figure 7**, illustrates the multivariate relationship among agronomic traits and their association with the different transplanting methods. The first two principal components (Dim1 and Dim2) explain 55.6% and 16.5% of the total variation, respectively, capturing the majority of trait variability. Traits such as plant height, tiller number, effective tillers, grain yield, test weight, and biomass yield are clustered on the right side of Dim1, signifying their strong positive loading on productivity-related components. SRI and mechanical transplanting appear grouped within this region, indicating strong alignment with high-yielding and vigor-related traits. Conversely, days to flowering and days to maturity load in a different direction, showing weak association with yield attributes. The ellipses show treatment clustering, with SRI forming a distinct grouping due to its superior performance across traits, whereas farmer practice and dry-bed method cluster toward lower-performing traits. This visual separation highlights the discriminative power of improved methods (SRI, mechanical) compared to traditional practices.

3.4.2. Correlation Matrix of Ten different Agronomic Traits of Spring Rice

The correlation heatmap (**Figure 8**), presents pairwise relationships between the ten measured traits, revealing strong and meaningful biological associations. Grain yield shows high positive correlations with biomass yield ($r \geq 0.90$), plant height, effective tillers per hill, tiller number, grains per panicle, and test weight, indicating that improvements in these variables directly enhance yield potential. Effective tillers show the strongest correlation with tiller number ($r \geq 0.96$), underscoring the importance of productive tillering in determining final yield. Days to flowering and days to maturity display negative or weak correlations with major yield-related traits, suggesting that earliness does not

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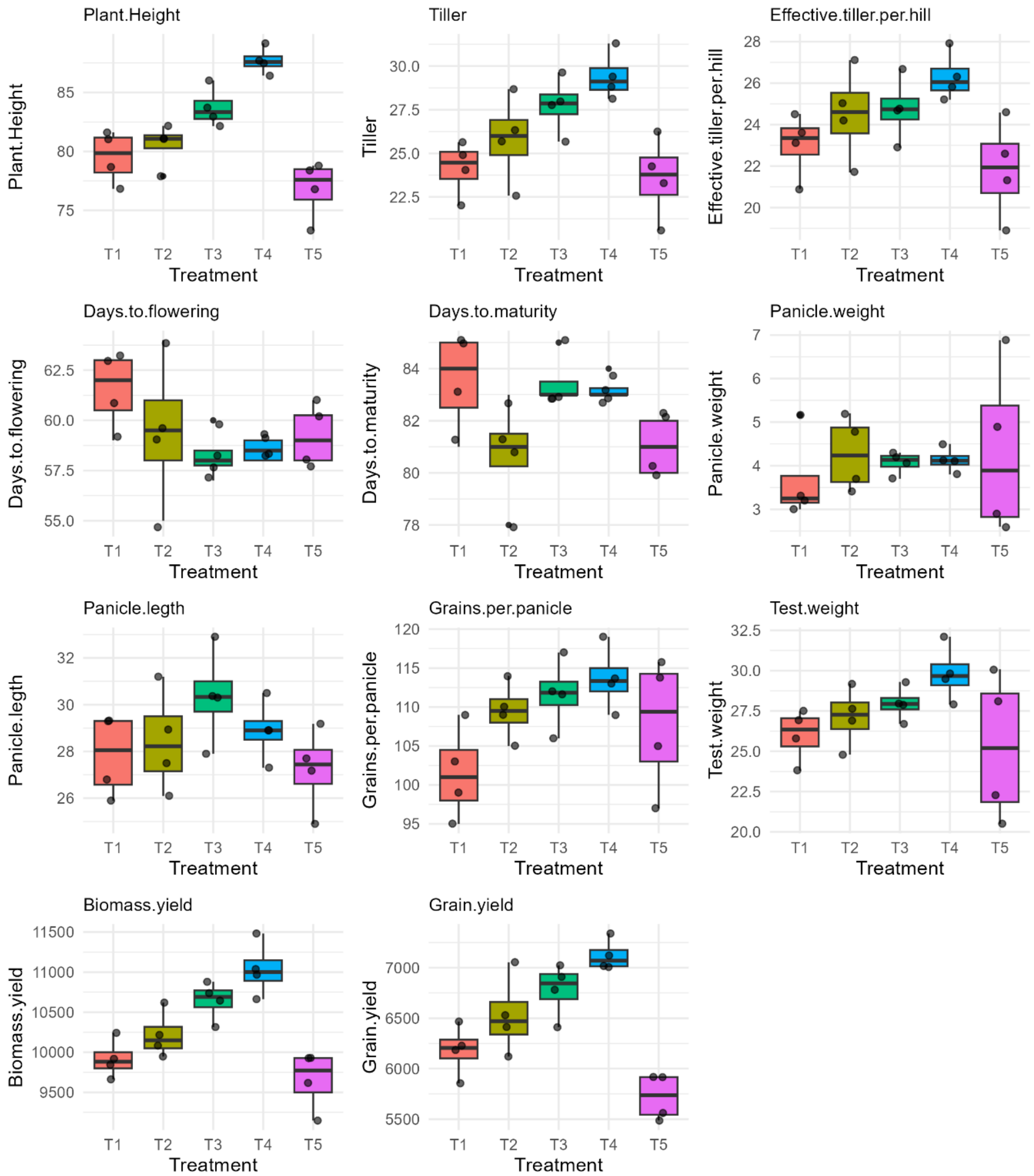
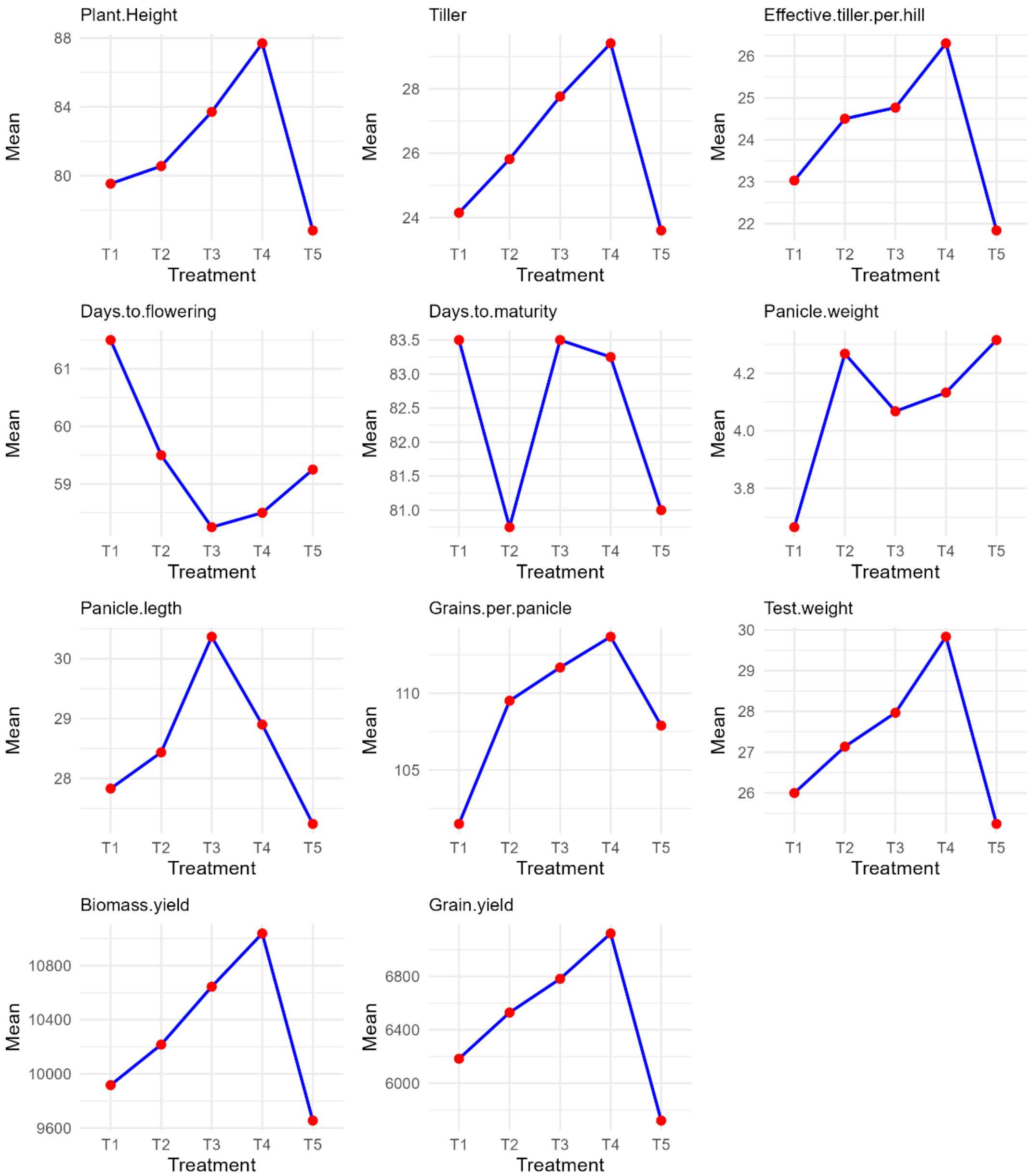


S.N.	Treatment	Notation
1	Farmer practices	T1
2	Traditional transplanting	T2
3	Mechanical Transplanting	T3
4	SRI	T4
5	Dry bed	T5

Figure 3. Boxplots showing the distribution of vegetative and yield traits of spring rice under five transplanting treatments.

necessarily translate to higher productivity in spring rice. The color gradient—from blue (negative) to deep orange (strong positive)—clearly visualizes these relationships, providing insights into how traits interact to influence overall rice performance under different transplanting methods.



S.N.	Treatment	Notation
1	Farmer practices	T1
2	Traditional transplanting	T2
3	Mechanical Transplanting	T3
4	SRI	T4
5	Dry bed	T5

Figure 4. Line graph of mean vegetative and yield traits of spring rice across five transplanting treatments

3.4.3. Radar Chart

The radar chart provides an intuitive, comparative visualization of how each transplanting method performs across all measured traits. The SRI method forms the largest and most outward-extending polygon, reflecting its superior performance in plant height, tillering ability, effective tillers, grain yield, biomass yield, grains per panicle, and panicle

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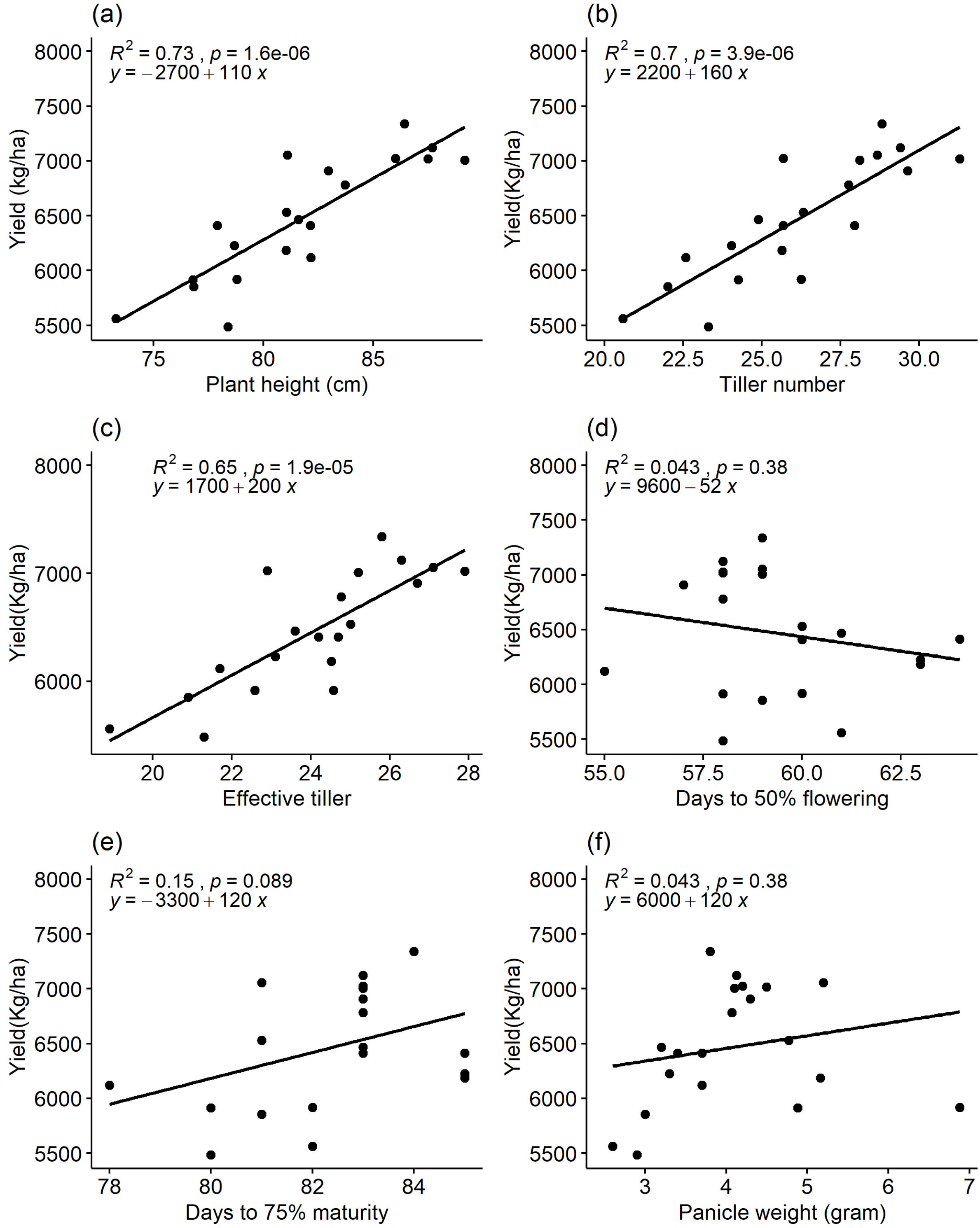

Figure 5. Coefficient of determination (R^2), Linear regression equation, and scatter diagram showing the fitted simple regression line of Y (Yield) on X ([a]Plant heights, [b]Number of tillers per hill, [c]Effective tiller per hill, [d]Days to 50% flowering, [e]Days to 75% maturity, [f]Panicle weights).

length. Mechanical transplanting also shows a broad coverage area, ranking second across most traits. Traditional and farmer-practice methods exhibit moderate performance, with smaller polygons reflecting reduced vigor and yield response. The dry-bed method consistently forms the smallest polygon, confirming its comparatively lower effectiveness across traits. This graphical representation highlights the holistic superiority of SRI and the consistent advantages

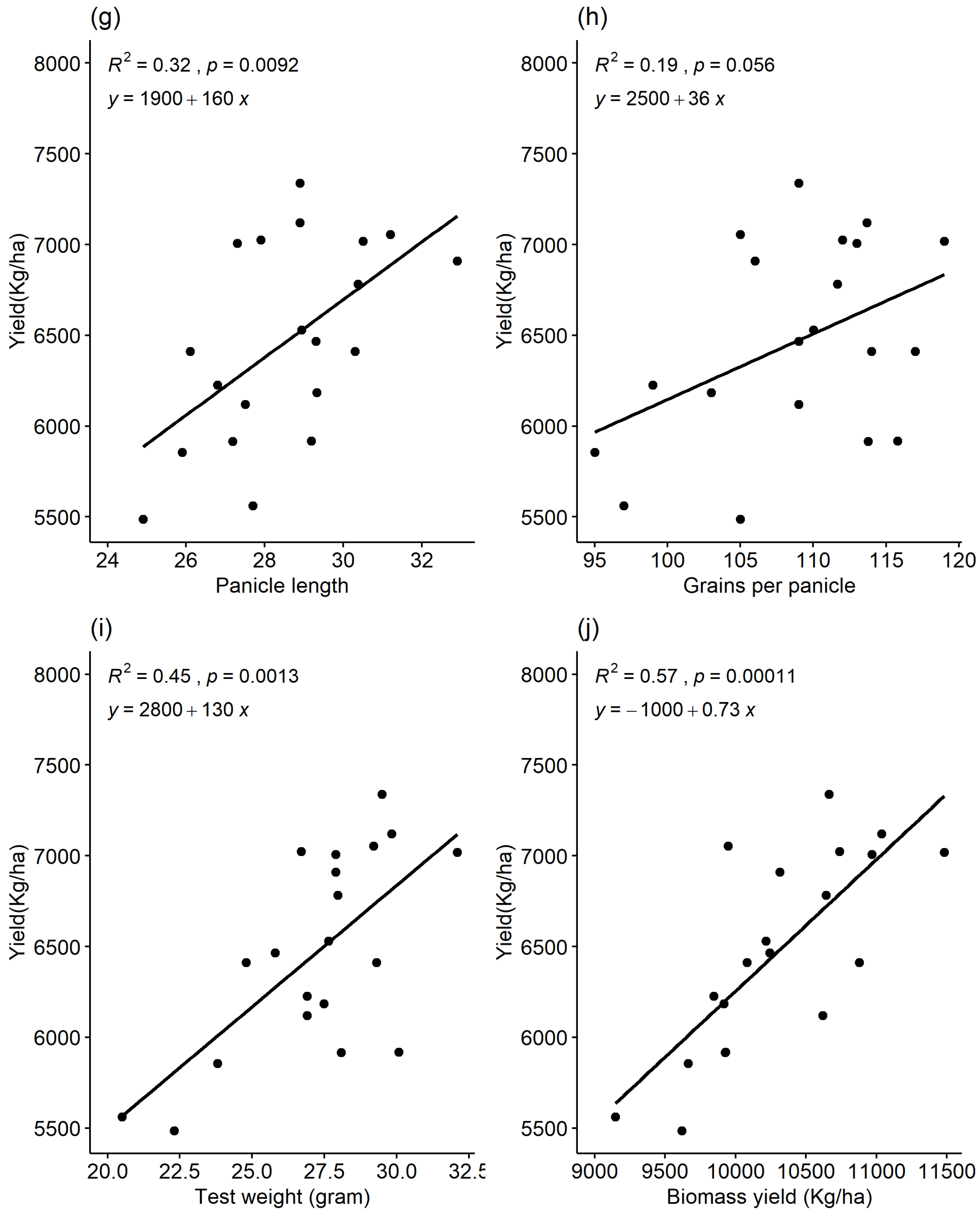

Figure 6. Coefficient of determination (R^2), Linear regression equation, and scatter diagram showing the fitted simple regression line of Y (Yield) on X ([g]panicle length, [h]grains per panicle, [i]test weight, [j]biomass yield).

of mechanical transplanting, emphasizing how transplanting method influences multiple interconnected agronomic traits simultaneously.

Together, **Figures 7**, **8**, and **9** provide a comprehensive multivariate understanding of how transplanting methods

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influence spring rice performance. The PCA biplot distinguishes high-performing methods based on trait vectors; the correlation matrix explains the statistical associations driving these differences; and the radar chart visually compares each method's trait expression. Collectively, these figures demonstrate that SRI and mechanical transplanting promote stronger trait interrelationships, higher productivity, and more desirable agronomic profiles compared to traditional practices.

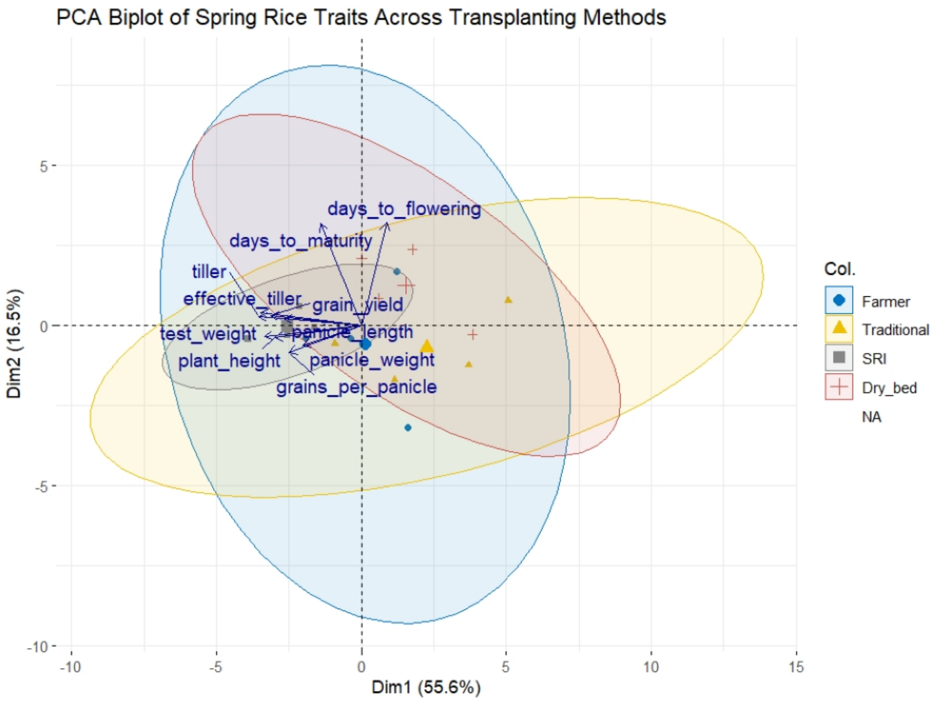

Figure 7. Principle Component analysis biplot of spring rice traits across transplanting method.

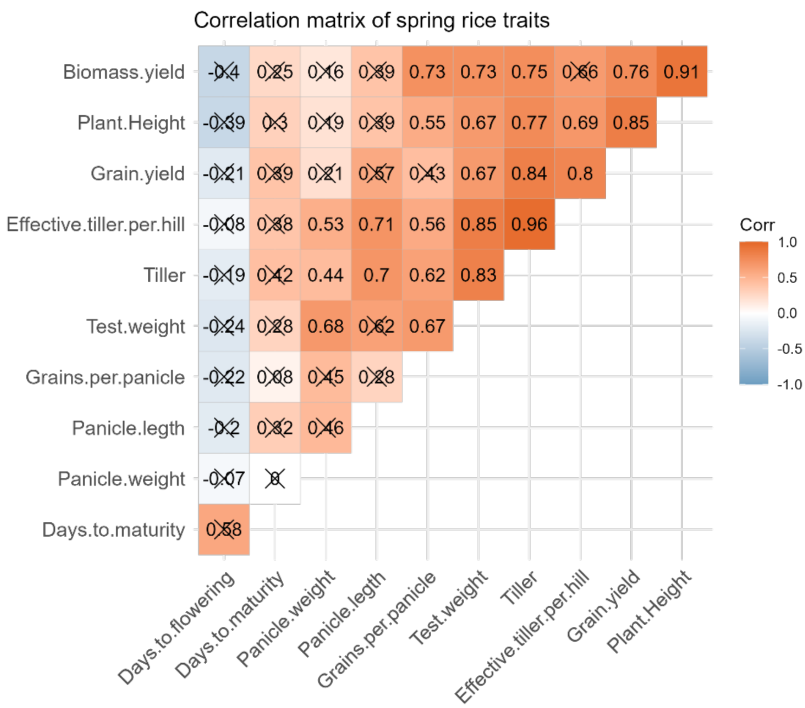

Figure 8. Correlation matrix of ten traits of spring rice.

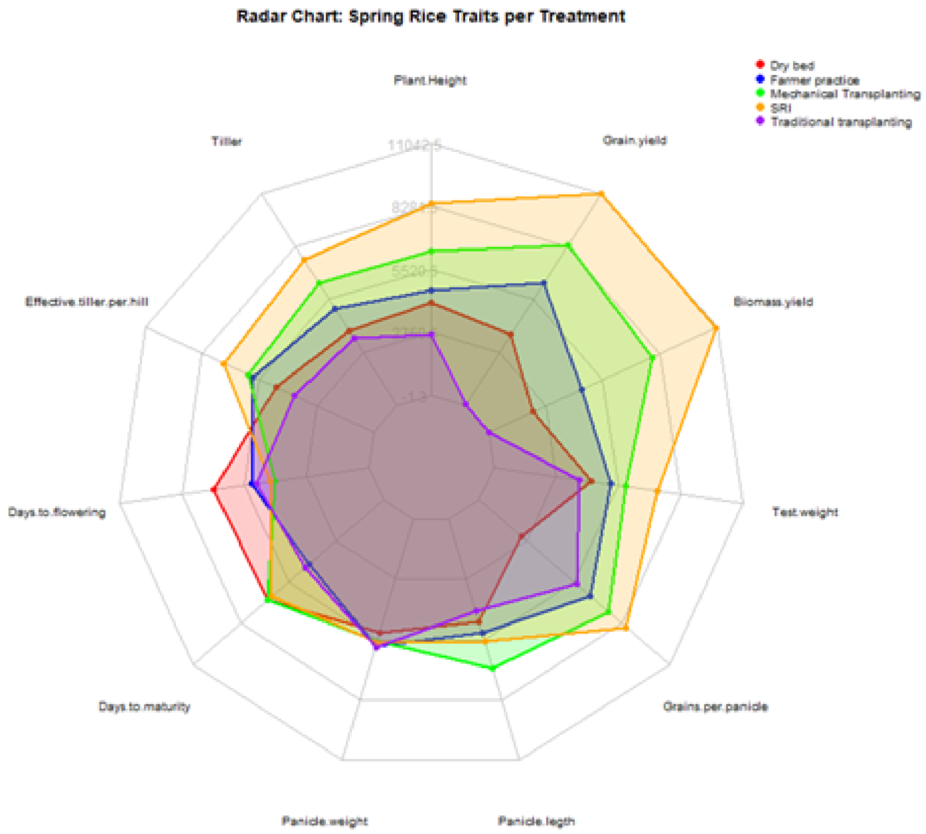

Figure 9. Radar chart of spring rice traits across transplanting methods.

4. Discussion

The present study showed that different transplanting methods significantly influenced the vegetative and reproductive traits of spring rice, and these findings align closely with earlier reports that highlight the advantages of improved planting systems over traditional methods. Similar to Bhandari et al. (2020) and Poudel et al. (2020), who observed greater plant height under SRI due to better soil aeration and nutrient uptake, this study found consistently taller plants under SRI, which can be mechanistically attributed to its wider spacing, reduced plant density, and intermittent irrigation that promote vigorous root growth and enhanced photosynthetic efficiency. The higher tiller production observed in SRI reflects trends documented by Mehata et al. (2023) and Kafle and Simkhada (2023), who emphasized that single-seedling planting and ample spacing reduce competition and support stronger tiller initiation and retention; similarly, in this study, the highest total and effective tillers were recorded under SRI, followed by mechanical transplanting, while the lowest were observed in traditional transplanting where overcrowding and inconsistent hill placement weakened plant performance. Mechanical transplanting also mirrored the findings of Awan et al. (2011), showing better performance than farmer practice due to uniform seedling placement and reduced transplant stress. The slight acceleration in flowering observed under SRI and mechanical transplanting in this study is consistent with the earlier establishment advantage noted by Poudel et al. (2020), while the longer maturity duration under these methods parallels the observations of Sharma et al. (2023), who reported prolonged grain filling in healthier and more vigorous rice crops. Panicle characteristics in this study further reflect earlier findings: the longer panicles under mechanical transplanting correspond with Regmi et al. (2020), who linked improved planting uniformity to better panicle development, while the higher grain number per panicle under SRI agrees with Shrestha et al. (2022), who attributed this to increased sink capacity driven by stronger panicle initiation under SRI conditions. The heavier test weight recorded in SRI treatments parallels the results of Mann and Dhillon (2023), who suggested that improved crop management enhances photosynthate partitioning, leading to better grain filling. Increases in biomass and grain yield under SRI in this study also correspond with reports by Poudel et al. (2020) and Acharya et al. (2024), who found that SRI and other modern transplanting methods improve canopy structure, root vigor, and nutrient-use efficiency, thereby enhancing yield potential. Overall, by integrating the mechanistic advantages of wider spacing, better root aeration, improved nutrient mobility, and reduced competition, both SRI and mechanical transplanting demonstrated clear superiority over traditional farmer practices, reaffirming conclusions from previous literature while providing strong evidence that these methods significantly enhance the growth and productivity of spring rice in Nepal.

5. Conclusion

The field experiment conducted at Belbari, Morang, clearly demonstrated that transplanting methods have a substantial influence on the vegetative and reproductive performance of spring rice. Among the five evaluated methods, the System of Rice Intensification (SRI) consistently outperformed all others, producing taller plants, a greater number of effective tillers, and the highest grain and biomass yields. These advantages are attributed to SRI's use of younger seedlings, wider spacing, and improved soil–water–aeration management, which collectively enhance root development, nutrient uptake, and overall physiological efficiency. Mechanical transplanting ranked second, providing better stand establishment and yield performance than traditional transplanting, farmer's practice, and the dry bed method. The observed differences among methods were largely driven by variations in transplanting stress, planting geometry, and aeration conditions. Based on these findings, the adoption of SRI or mechanical transplanting is strongly recommended for farmers in Nepal's eastern Terai to improve productivity and resource-use efficiency. To ensure wider uptake, extension services and local authorities should promote these techniques through field demonstrations, farmer training, and technical assistance. Additionally, supportive policies that encourage mechanization and modern transplanting practices will be essential for enhancing the sustainability, profitability, and long-term resilience of Nepal's rice production sector.

Authors' Contributions

Conceptualization: Sanskaran Timsina, Rupesh Kumar Mehta, Chetana Roy; Data curation: Sanskaran Timsina, Rabin Adhikari, Nibesh Kumar Yadav, Abhishek Chaudhary, Chetana Roy, Rupesh Kumar Mehta; Funding acquisition: Sanskaran Timsina, Rupesh Kumar Mehta; Investigation: Dreesti Wasti; Methodology: Sanskaran Timsina, Rabin Adhikari, Nibesh Kumar Yadav, Abhishek Chaudhary, Chetana Roy, Rupesh Kumar Mehta; Resources: Sanskaran Timsina; Software: Rupesh Kumar Mehta, Chetana Roy; Supervision: Dreesti Wasti; Validation: Dreesti Wasti; Visualization: Rupesh Kumar Mehta; Writing – original draft: Rupesh Kumar Mehta, Chetana Roy, Sanskaran Timsina; Writing – review & editing: Sanskaran Timsina, Rupesh Kumar Mehta, Dreesti Wasti.

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Declarations

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: This study did not involve human or animal subjects, and no institutional or ethical approval was required.

Data Availability/Sharing: The datasets used and analysed during the current study will be made available from the corresponding author upon a reasonable request.

Supplementary Information Availability: Not applicable.

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