Impact of Nitrogen Variability on Yield Dynamics and Economics Viability of Transplanted and Direct Seeded Rice

ABSTRACT

Efficient nitrogen (N) management plays a critical role in optimizing rice yield and ensuring economic sustainability. This study evaluates the impact of variable nitrogen levels on the yield dynamics and economic viability of transplanted rice (TPR) and direct seeded rice (DSR). Field experiments were conducted in randomised complete block design with seven N treatments (0, 40, 80, 120, 160, 200 and 240 kg N/ha) applied in a split application method. Key yield components like grain and straw yields were recorded. Economic analysis included cost of cultivation, gross return, net return, and benefit-cost ratio (BCR). Results showed that nitrogen significantly influenced yield in both TPR and DSR systems, with optimal N levels identified as 160 kg N/ha for TPR and DSR. Beyond these levels, yields declined, highlighting the importance of precise N management. TPR recorded higher grain and straw yields but incurred greater production costs due to labor-intensive practices and higher water requirements. In contrast, DSR offered lower input costs and higher economic returns at comparable yield levels, achieving a maximum BCR as 2.00 at 120 kg N/ha. This study emphasizes the importance of tailoring N application rates to specific crop establishment methods to optimize yield and economic returns. The findings offer practical insights for sustainable rice production, reducing input costs while minimizing environmental N losses. Further research on real-time N management strategies for DSR is recommended to enhance its efficiency and adaptability.

Keywords: Nitrogen management, Yield dynamics, Economics, Transplanted rice, Direct seeded rice

1. INTRODUCTION

Rice (Oryza sativa L.) is a staple food for more than half of the global population, playing a crucial role in ensuring food security, especially in Asia (Chowdhury et al., 2023; Sunil Kumar et al., 2024). With rising population pressures and limited arable land, enhancing rice productivity while ensuring sustainability has become a priority for researchers and policymakers (Kumari et al., 2023). Nitrogen (N) is one of the most critical macronutrients for rice production, significantly influencing plant growth, yield, and grain quality (Chowdhury et al., 2024a). However, nitrogen use efficiency (NUE) in rice production remains alarmingly low, often ranging from 30% to 50%, with substantial losses due to leaching, volatilization, and denitrification (Chowdhury et al., 2024b). Inefficient N management not only escalates production costs but also contributes to environmental pollution, including greenhouse gas emissions and water contamination (Kurmi et al., 2023).

Rice is traditionally grown using two primary crop establishment methods: transplanted rice (TPR) and direct-seeded rice (DSR). Transplanted rice, the conventional method, involves raising seedlings in a nursery and transplanting them into puddled fields. While TPR is known for effective weed control and higher yields, it is labour-intensive and requires significant water inputs. In contrast, DSR, which involves sowing seeds directly into the field, has emerged as a labour- and water-saving alternative (Pradhan et al., 2024; Jha et al., 2024; Chowdhury et al., 2025). Despite its advantages, DSR is often associated with lower yields and greater vulnerability to weed infestation and nutrient imbalances (Liu et al., 2015; Kaur et al., 2017). The choice of an appropriate N management strategy for these two systems is crucial to optimize their productivity and economic returns.

Nitrogen variability, in terms of both application rates and timing, has a profound impact on rice growth and yield (Djaman et al., 2018). Excessive nitrogen application often leads to lodging, delayed maturity, and reduced grain quality, while suboptimal application results in poor vegetative growth and yield (Patra et al., 2023; Chowdhury et al., 2023b; Kushwah et al., 2024a). Balancing nitrogen levels is particularly challenging in DSR due to its distinct physiological and environmental responses compared to TPR. Understanding how different N levels influence yield dynamics in TPR and DSR is essential to develop tailored nutrient management strategies for sustainable rice production (Chowdhury et al., 2024c; Malkani et al., 2024).

Economic viability is another critical aspect influencing the adoption of nitrogen management practices. Farmers are increasingly prioritizing strategies that enhance profitability by reducing input costs while maintaining or improving yields (Kushwah et al., 2024b; Madhusudan et al., 2024). TPR, although higher-yielding, incurs greater costs due to labour-intensive practices and higher water usage. On the other hand, DSR, with its lower production costs, presents an economically attractive option but often requires more precise N management to achieve comparable yields (Kushwah et al., 2024c). A comprehensive analysis of the economic returns under varying N levels for both establishment methods is necessary to identify the most viable and sustainable practice.

This study aims to evaluate the impact of nitrogen variability on yield dynamics and the economic viability of TPR and DSR systems. By comparing the performance of TPR and DSR under variable nitrogen levels, this research provides valuable insights for optimizing N management strategies tailored to each establishment method. The findings of this study are expected to contribute to the growing body of knowledge on sustainable rice production practices, addressing the twin challenges of food security and environmental sustainability. By highlighting the interplay between nitrogen variability, yield dynamics, and economic returns, the study aims to guide farmers and policymakers toward adopting efficient and cost-effective nitrogen management practices.

2. MATERIALS AND METHODS

2.1 Experimental site

The experimental study was conducted at the research farm of the Indian Council of Agricultural Research - Indian Agricultural Research Institute (ICAR-IARI), New Delhi, India. The farm is located at 28.63°N latitude, 77.16°E longitude, and an elevation of 228.6 meters above mean sea level. The region falls under a semi-arid, subtropical climate characterized by hot summers, cool winters, and a monsoonal rainfall pattern. The soil of the experimental site is classified as sandy loam, with moderate fertility and good drainage properties, making it suitable for rice cultivation under both transplanted and direct-seeded systems. The average annual rainfall of the area is approximately 650-700 mm, the majority of which is received during the monsoon season (June to September). The experimental site is equipped with facilities for controlled irrigation and modern agricultural practices, providing an ideal setup for conducting field trials.

2.2 Rice cultivation methods

2.2.1 Transplanted rice (TPR)

The transplanting process of rice involved several steps. Initially, rice seeds were sown in nursery, where they germinated and grew into young seedlings. Once the seedlings reached a certain size, usually around 21-25 days old, they were carefully uprooted from the nursery and transplanted into the prepared paddy fields. Transplanting was done manually, with workers planting the seedlings at uniform intervals in rows that are submerged in water (Fig. 1). For transplanted rice, the seedbed preparation involved two passes of a disc harrow, followed by one pass of a cultivator with a wooden plank, and finally the puddling operation.

Fig. 1 Manual transplanting of rice seedlings

2.2.2 Direct seeded rice (DSR)

Direct seeding of rice involved sowing rice seeds directly into prepared fields without the intermediate step of transplanting seedlings from a nursery. For direct-seeded rice, seedbed preparation involved only two passes of a disc harrow and one pass of a cultivator with a wooden plank. Direct seeding was carried out using a tractor-operated 9-row DSR planter immediately after seedbed preparation (Fig. 2). Prior to sowing, rice seeds were treated with Carbendazim 50 WP (Bavistin 50WP) at a rate of 2 g/lit of water per kilogram of seeds to control fungal diseases, tip burn, black spot, and collar spot. The treated PB-1509 rice seeds are sown at a rate of 20 kg per hectare.

Fig. 2 Direct seeding of rice with tractor drawn DSR planter

2.3 Experimental design and details

The experiment was laid out in a randomized complete block design (RCBD) with three replications to ensure statistical reliability and minimize variability in results. Each treatment was assigned randomly within the blocks to reduce the influence of field heterogeneity. The experimental plots were of uniform size, measuring 5 m × 4 m (20 m^2). Standard agronomic practices were followed for land preparation, irrigation, and pest management. For the TPR method, 25-day-old seedlings were transplanted manually with a spacing of 20 cm × 15 cm. In the DSR method, seeds were directly sown in well-prepared plots using a row spacing of 20 cm. To minimize external variability, the plots were irrigated uniformly based on the crop's water requirements. Proper bunds and channels were maintained to avoid nutrient and water movement between plots.

2.4 Fertilizer application

The study involved two rice establishment methods i.e., transplanted rice (TPR) and direct seeded rice (DSR) and seven nitrogen (N) levels: 0, 40, 80, 120, 160, 200, and 240 kg N/ha (Table 1). Nitrogen was applied in a split application, with 50% of the total N dose applied as basal (at sowing/transplanting), 25% at the tillering stage, and the remaining 25% at the panicle initiation stage. By varying the doses within this range, the experiment was aimed to assess the response of the rice plants to increasing amounts of fertilizer and determine the optimal dosage that would maximize yield and overall plant health. This range allows for a comprehensive analysis of the impact of fertilizer on both cultivation methods and provides valuable insights for agricultural practices and crop management. The specific nutrient elements and their ratios in the fertilizer were determined based on recommended practices for rice cultivation in the region. Fertilizer application methods, including basal application and top-dressing, followed the standard practices adopted by farmers in the study area, ensuring consistency and relevance to practical agricultural operations. Phosphorus (P) and potassium (K) were applied uniformly to all plots at the recommended rates of 60 kg P_2O_5/ha and 60 kg K_2O/ha, respectively.

Table 1 Details of the applied N treatments in TPR and DSR

N Treatments	**N application**
Control	No doses
33.33% of RDN	40 kg N/ha
66.67% of RDN	80 kg N/ha
Recommended dose of nitrogen (RDN)	120 kg N/ha
133.33% of RDN	160 kg N/ha
166.67% of RDN	200 kg N/ha

200% of RDN	240 kg N/ha

2.5 Yield assessment for TPR and DSR cultivation

Yield assessment was conducted to evaluate the impact of variable N levels on the grain and straw yields of transplanted rice (TPR) and direct-seeded rice (DSR). At physiological maturity, plants from each plot were harvested manually, leaving a buffer zone around the edges to avoid border effects. The harvested produce was then sun-dried for a few days before threshing to separate the grains from the straw. Grain yield was recorded after cleaning and drying the grains to a uniform moisture content of 14%, which is the standard for rice storage and marketing. Straw yield was determined by weighing the dried plant residues after grain separation. The grain and straw yields were expressed in kilograms per hectare (kg/ha).

2.6 Cost evaluation of TPR and DSR cultivation

The cost evaluation of transplanted rice (TPR) and direct seeded rice (DSR) cultivation was carried out to determine the economic viability of both systems under varying nitrogen (N) levels. The total cost of cultivation for each treatment was calculated by considering all major inputs, including seeds, fertilizers, irrigation, labor, and machinery usage. For TPR, the costs included nursery preparation, seedling transplantation, irrigation, and labour for transplanting and weed control. For DSR, the costs associated with direct seeding operations, irrigation, and weed management were recorded. Fertilizer costs were calculated based on the quantity of nitrogen, phosphorus, and potassium applied per treatment. Irrigation costs were computed by considering the amount of water applied and the energy required for pumping. The cost of plant protection measures, including pesticides and herbicides, was also included. Economic returns were assessed by calculating the gross income, net income, and benefit-cost ratio (BCR) for each treatment. Gross income was determined based on the grain and straw yields and their respective market prices. Net income was derived by subtracting the total cost of cultivation from the gross income. The BCR, an indicator of economic efficiency, was calculated as the ratio of gross income to the total cost of cultivation.

2.7 Statistical analysis

The Duncan's Multiple Range Test (DMRT) was conducted using SPSS software to compare the means of yield and economic parameters across different nitrogen levels and crop establishment methods. The test helped identify significant differences between treatment combinations at a 5% significance level ($p \leq 0.05$), enabling a clear understanding of the effects of nitrogen variability on yield and cost economics.

3. RESULTS AND DISCUSSION

3.1 Impact of nitrogen levels on yield dynamics of TPR

3.1.1 Grain yield of TPR

The grain yield of transplanted rice (TPR) was significantly influenced by varying nitrogen application rates (Fig. 3). The results showed a clear upward trend in yield as the N dose increased from 0 kg N/ha to 160 kg N/ha, after which the yield declined with higher nitrogen levels. The lowest grain yield (2455 kg/ha) was observed in the control treatment (0 kg N/ha), indicating the critical role of nitrogen in enhancing productivity. Yield increased progressively with N application, reaching a maximum of 4886 kg/ha at 160 kg N/ha. Beyond this optimum level, further increases in nitrogen dose (200 kg N/ha and 240 kg N/ha) led to a slight decline in grain yield, with values of 4412 kg/ha and 4408 kg/ha, respectively. The diminishing returns at higher N levels could be attributed to nitrogen saturation, leading to luxury consumption or possible nitrogen losses through leaching or volatilization. These findings highlight 160 kg N/ha as the most efficient nitrogen dose for maximizing grain yield in TPR under the given experimental conditions.

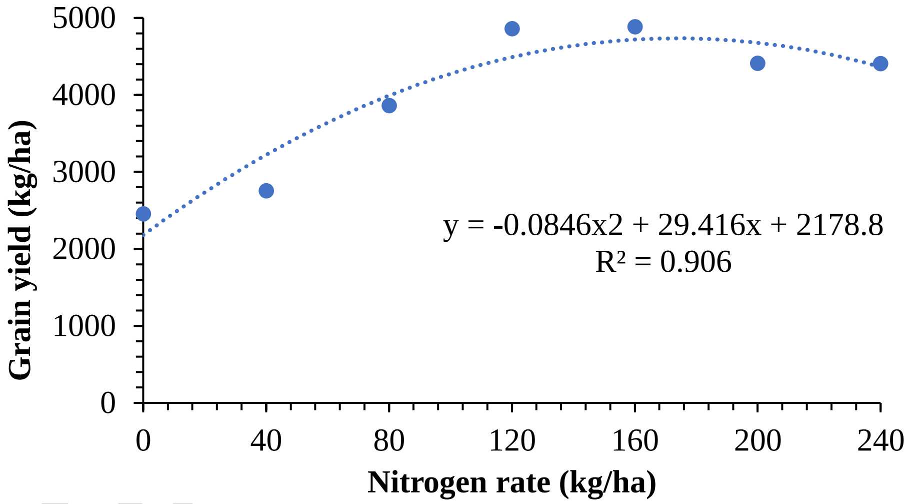

Fig. 3 TPR Grain yield at varying N levels

3.1.2 Straw yield of TPR

The straw yield of transplanted rice (TPR) showed a positive response to increasing nitrogen (N) application rates (Fig. 4). A steady increase in straw yield was observed across all N doses, with the highest yield recorded at the maximum nitrogen application of 240 kg N/ha. The lowest straw yield (4601 kg/ha) was obtained in the control treatment (0 kg N/ha), indicating the substantial influence of nitrogen on vegetative biomass production. Straw yield increased progressively with N application, reaching 7681 kg/ha at 160 kg N/ha. Beyond this level, straw yield continued to increase slightly, with 7778 kg/ha and 7856 kg/ha observed at 200 kg N/ha and 240 kg N/ha, respectively. The incremental rise in straw yield even at higher nitrogen doses suggests that vegetative growth in TPR is less prone to saturation compared to grain yield.

These results highlight the consistent role of nitrogen in enhancing straw biomass, with maximum production observed at the highest nitrogen application of 240 kg N/ha.

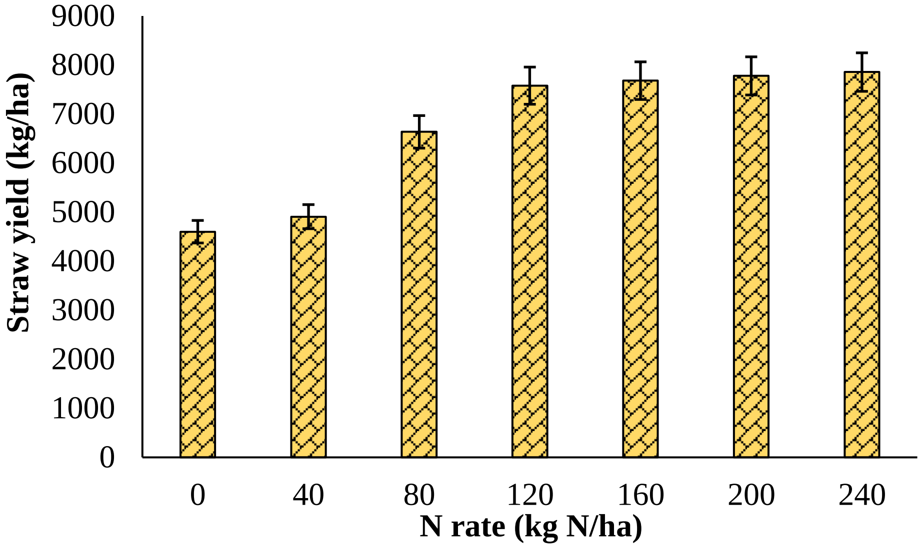

Fig. 4 Straw yield of TPR at varying N levels

3.2 Impact of nitrogen levels on yield dynamics of DSR

3.2.1 Grain yield of DSR

The grain yield of direct-seeded rice (DSR) exhibited a significant response to varying nitrogen application rates, with a similar trend to TPR (Fig. 5). Yield increased consistently as the nitrogen dose increased from 0 kg N/ha to 160 kg N/ha, followed by a decline at higher N levels. The lowest yield (2315 kg/ha) was recorded in the control treatment (0 kg N/ha), emphasizing the necessity of nitrogen application for optimal DSR productivity. Grain yield peaked at 160 kg N/ha with 4488 kg/ha, demonstrating the maximum nitrogen use efficiency at this level. Beyond 160 kg N/ha, yield declined slightly, with 4156 kg/ha and 4080 kg/ha observed at 200 kg N/ha and 240 kg N/ha, respectively. The yield reduction at higher N levels suggests nitrogen saturation or losses through volatilization, denitrification, or leaching in the direct-seeded system. These results highlight that 160 kg N/ha is the most effective nitrogen dose for achieving maximum grain yield in DSR under the experimental conditions.

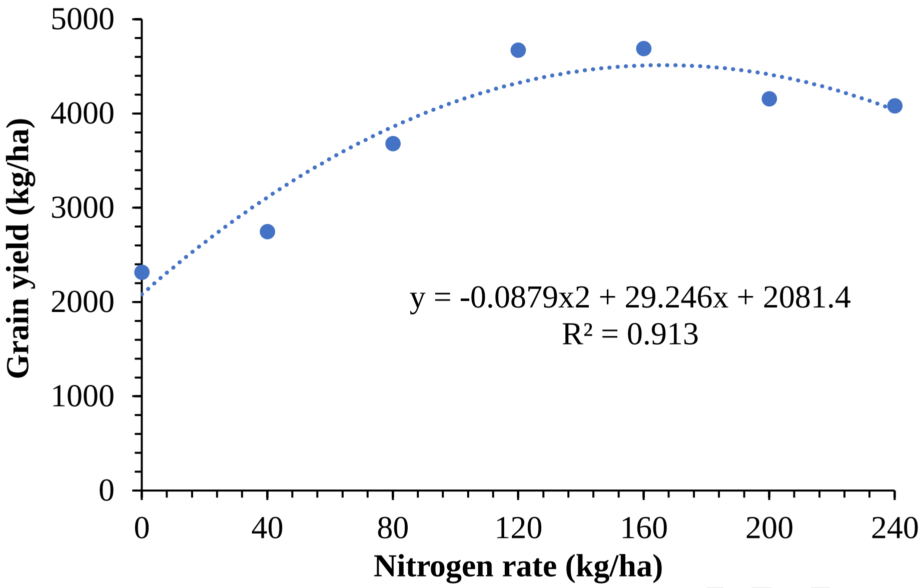

Fig. 5 DSR Grain yield at varying N levels

3.2.2 Straw yield of DSR

The straw yield of direct seeded rice (DSR) increased consistently with higher N application rates, showing a positive response across all treatments (Fig. 6). The highest straw yield was observed at the maximum nitrogen application of 240 kg N/ha. The lowest straw yield (4442 kg/ha) was recorded in the control treatment (0 kg N/ha), highlighting the critical role of nitrogen in promoting vegetative growth in DSR. With increasing N levels, straw yield improved steadily, reaching 7009 kg/ha at 160 kg N/ha. Further increases in N application resulted in a marginal rise in straw yield, with 7246 kg/ha and 7269 kg/ha observed at 200 kg N/ha and 240 kg N/ha, respectively. The continued increase in straw yield at higher N doses suggests that vegetative growth in DSR is influenced by nitrogen even beyond the optimal level for grain yield. These results indicate that nitrogen application significantly enhances straw biomass, with maximum production achieved at the highest tested nitrogen rate of 240 kg N/ha.

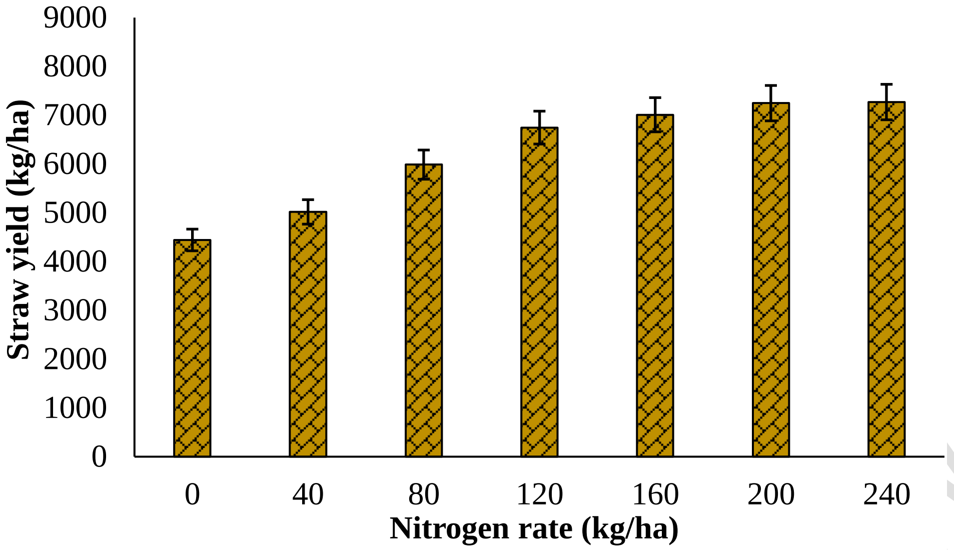

Fig. 6 Straw yield of DSR at varying N levels

3.3 Economic viability of TPR and DSR

The economic viability of transplanted rice (TPR) and direct-seeded rice (DSR) was evaluated by analysing the cost of production, gross returns, net returns, and benefit-cost (B:C) ratios across varying nitrogen (N) doses. The cost of production increased consistently with higher N doses in both TPR and DSR systems, primarily due to the additional input costs associated with fertilizer application. However, DSR demonstrated consistently lower production costs compared to TPR, with savings ranging between ₹7198 and ₹7199 per hectare, attributed to reduced labour and water requirements. Gross returns for both TPR and DSR increased with N application, reaching their peak at 160 kg N/ha, where TPR recorded ₹114,167.50 ha^{-1}, and DSR achieved ₹104,851.70 ha^{-1}. However, further increases in N application beyond 160 kg/ha resulted in a slight decline in gross returns, likely due to diminishing yield response and higher production costs. Net returns followed a similar trend, with the highest values observed at 160 kg N/ha for TPR (₹71,790.15 ha^{-1}) and DSR (₹69,672.50 ha^{-1}). At lower nitrogen doses (0–80 kg N/ha), DSR showed higher net returns than TPR, attributed to its cost-efficient production system. The benefit-cost ratio further highlighted the economic efficiency of DSR, which consistently outperformed TPR across all nitrogen levels. The highest B:C ratios were observed at 120 kg N/ha for both systems, with DSR achieving a maximum of 2.00 compared to 1.71 for TPR. DSR exhibited superior economic performance, with a B:C ratio of 1.98 at 160 kg N/ha compared to 1.69 for TPR.

These findings demonstrate that nitrogen management significantly influences the economic viability of TPR and DSR systems. While TPR achieved slightly higher gross returns at optimal nitrogen levels, DSR was more cost-effective and economically sustainable due to its lower production costs and higher resource-use efficiency. The decline in returns at higher nitrogen doses emphasizes the need for precise nitrogen application to optimize both yield and economic gains. These results suggest that DSR, with its cost advantages and higher B:C ratios, offers a more sustainable and economically viable alternative to TPR, particularly under lower nitrogen input conditions.

Table 2 Cost economics (2-year mean basis) of TPR and DSR

N Dose (kg N/ha)	Cost of production (₹/ha)		Gross return (₹/ha)		Net return (₹/ha)		Benefit-cost ratio	
	TPR	DSR	TPR	DSR	TPR	DSR	TPR	DSR
0	40513.33	33315.24	57992.50^{e}	54838.33^{e}	17479.17^{e}	21523.33^{e}	0.43^{e}	0.65^{e}
40	40979.17	33780.83	64900.83^{d}	64787.50^{d}	23920.83^{d}	31006.67^{d}	0.58^{d}	0.92^{d}
80	41445.83	34246.67	90892.50^{c}	86163.33^{c}	49447.50^{c}	51915.83^{c}	1.19^{c}	1.52^{c}
120	41911.67	34713.33	113418.30^{a}	104315.80^{a}	71506.67^{a}	69602.50^{a}	1.71^{a}	2.00^{a}
160	42377.50	35179.15	114167.50^{a}	104851.70^{a}	71790.15^{a}	69672.50^{a}	1.69^{a}	1.98^{a}
200	42844.17	35645.89	104113.30^{b}	97762.50^{b}	61269.17^{b}	62116.67^{b}	1.43^{b}	1.74^{b}
240	43310.25	36111.67	103959.20^{b}	96150.83^{b}	60649.17^{b}	60040.25^{b}	1.40^{b}	1.66^{b}

Note: The MSP of rice and straw selling price were taken as 2381 ₹/Quintal and 100 ₹/Quintal respectively for calculating the gross return. Means with similar letters within the same column do not exhibit statistically significant differences at a significance level of $p \leq 0.05$ as determined by the DMRT.

4. CONCLUSIONS

The findings of this study underscore the significant influence of nitrogen levels on the yield dynamics and economic viability of transplanted rice (TPR) and direct-seeded rice (DSR) systems. The results revealed a clear trend where both TPR and DSR exhibited enhanced grain and straw yields up to an optimal nitrogen application rate of 160 kg N/ha, beyond which yields declined. This highlights the critical importance of precise nitrogen management in optimizing productivity. Notably, TPR consistently outperformed DSR in grain yield across all nitrogen levels, reflecting its superior capacity for nutrient uptake and utilization. However, DSR demonstrated greater economic efficiency due to its reduced labour and water requirements, making it a cost-effective alternative for resource-constrained farmers. The economic analysis further reinforced the viability of DSR under appropriate nitrogen management. The cost evaluation revealed lower production costs for DSR compared to TPR, driven primarily by the elimination of labour-intensive transplanting and nursery preparation. Despite slightly lower yields, DSR achieved comparable or higher net returns and benefit-cost ratios, particularly at nitrogen application rates of 120-160 kg N/ha. This suggests that DSR can be a sustainable alternative to TPR when coupled with precise nutrient management practices.

This study provides valuable insights into the interplay between nitrogen variability, yield dynamics, and economic viability in rice production systems. The findings emphasize the need for site-specific nitrogen management strategies tailored to the physiological and economic characteristics of TPR and DSR. For policymakers and farmers, the study highlights the potential of DSR as a labor- and water-saving alternative, provided that optimal nitrogen levels are maintained. Future research should focus on integrating precision agriculture technologies, such as sensor-based nitrogen application, to further enhance nitrogen use efficiency and sustainability in rice cultivation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist

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