E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(12): 236-242
Received: 13-09-2025
Accepted: 17-10-2025

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Influence of methods of crop establishment and nitrogen management practices on the growth and yield performance of *Kharif* rice

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i12d.4369

Abstract
A field experiment was conducted during the *kharif* seasons of 2023 and 2024 at the Agronomy Research Farm, ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad, Telangana, to evaluate the influence of crop establishment methods and nitrogen management practices on the growth and yield of rice. The study was laid out in a split-plot design with three replications, comprising three establishment methods, transplanting (M_1), mechanical transplanting (M_2) and wet direct-seeded rice (M_3) in the main plots, and five nitrogen management practices, 100% RDN through urea (S_1), LCC-based nitrogen management (S_2), 75% RDN + nano urea sprays (S_3), 100% RDN through slow-release urea (S_4) and control (S_5) in the subplots. Data were analysed using ANOVA, and treatment means were compared at the 5% level of significance ($P = 0.05$).
Across both years and pooled *kharif* data, significant treatment effects emerged from 60 DAS onward. Wet direct-seeded rice (M_3) and mechanical transplanting (M_2) consistently recorded higher plant height, tiller production, dry matter accumulation, grain yield and straw yield than transplanting (M_1). Among nitrogen treatments, slow-release urea (S_4) and LCC-based management (S_2) produced the highest yields, highlighting the importance of synchronized nitrogen availability. Conventional 100% RDN (S_1) through urea and reduced basal nitrogen combined with nano urea (S_3) sprays resulted in moderate performance, while the control (S_5) recorded the lowest values for all parameters. Harvest index remained unaffected by establishment methods or nitrogen practices. Overall, the results indicate that integrating wet direct-seeded rice or mechanical transplanting with slow-release urea or LCC-based nitrogen management is a productive and sustainable strategy for improving *kharif* rice performance.

Keywords: Kharif rice, crop establishment methods, nitrogen management

1. Introduction
Rice (*Oryza sativa* L.) remains one of the world's most important cereal crops and serves as the staple food for more than half of the global population. Its significance is even greater in Asian countries, where rice contributes substantially to caloric intake and rural livelihoods. In India, rice cultivation during the *kharif* season is of major importance because it coincides with the southwest monsoon, which supplies nearly 70% of the annual rainfall. However, *kharif* rice production is increasingly challenged by monsoon irregularities such as delayed onset, prolonged dry spells, and sudden heavy rainfall events, all of which negatively affect crop establishment, nutrient uptake, and final yields. Therefore, developing climate-resilient rice production strategies is essential to safeguard food security in the region.
Crop establishment plays a vital role in determining early plant vigour, nutrient uptake, root development, and overall crop performance. Traditional puddled transplanting remains widely practiced but is labour-intensive, water-demanding, and highly sensitive to monsoon timing. Mechanical transplanting offers advantages such as uniform planting and reduced labour dependency, while wet direct-seeded rice has emerged as a promising alternative due to its lower water requirement and ability to facilitate quicker sowing after rainfall. Studies have reported that direct-seeded rice can reduce water use and methane emissions while maintaining comparable yield levels under suitable management (Kumar and Ladha, 2011) [10]; (Sander *et*

al., 2017) [24]. These improved establishment methods provide viable options for increasing the resilience of *kharif* rice under changing climatic conditions.

Nitrogen is the most yield-limiting nutrient in rice cultivation. Despite high fertilizer use, nitrogen-use efficiency (NUE) often remains below 40% due to losses through volatilization, leaching, and denitrification. Such losses intensify during the *kharif* season because heavy rains promote nutrient leaching, while dry spells restrict plant uptake. Therefore, efficient nitrogen management practices are crucial for improving nutrient recovery, yield stability, and environmental sustainability. Improved NUE also offers economic benefits by reducing fertilizer requirements, a critical factor in resource-poor farming systems.

Several nitrogen management strategies have been developed to address these challenges. The Leaf Colour Chart (LCC) is a simple, farmer-friendly tool that helps synchronize nitrogen application with crop demand, often reducing nitrogen use without affecting productivity (Balasubramanian *et al*., 1999) [2]; (Singh *et al*., 2002) [29]. Slow-release nitrogen fertilizers, such as silicon-coated urea, minimize nutrient losses by providing gradual nitrogen availability, thereby improving plant uptake efficiency—especially under erratic *kharif* rainfall (Sun *et al*., 2020) [30]. Review studies have shown that such improved nitrogen management strategies significantly enhance nutrient-use efficiency and grain yield across cropping systems (Chivenge *et al*., 2021) [5]. These innovations highlight the need for integrating appropriate nitrogen management practices with efficient crop establishment methods.

Considering the increasing frequency of climatic abnormalities during the *kharif* season and the need for sustainable intensification of rice systems, a comprehensive evaluation of establishment methods and nitrogen management practices is warranted. The present study was therefore undertaken to assess how different crop establishment methods combined with nitrogen management strategies influence the growth performance and yield of *kharif* rice.

2. Materials and Methods

2.1 Experimental Site and Soil Characteristics

The field experiment was carried out during the *kharif* seasons of 2023 and 2024 at the Agronomy Research Farm, ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad, Telangana, India (17.32° N, 78.38° E; 542 m above mean sea level). The experimental site represents the semi-arid tropical climate with hot summers, mild winters, and an average annual rainfall of about 850 mm, the majority received through the southwest monsoon. Soil samples were collected randomly from the experimental field at a depth of 0-30 cm prior to the initiation of the experiment and analysed for their physico-chemical properties following standard procedures. The soil of the experimental site was classified as clay loam in texture and exhibited a slightly alkaline reaction. The organic carbon content was low, while available nitrogen was also in the low range. The soil contained medium levels of available phosphorus and higher levels of available potassium. These characteristics were consistently recorded during both the cropping years (2023 and 2024).

2.2 Weather During Crop Growth Period

The experiment was conducted during *kharif* seasons of 2023 and 2024, under varying climatic conditions. During *kharif* 2023 (06 August-31 December), the weekly mean maximum and minimum temperatures ranged from 27.7-33.1°C and 15.8-23.7 °C, respectively. Relative humidity varied between 55.2-86.2%, with mean sunshine hours of 5.9 h day^{-1}, wind speed of 4.6 km hr^{-1}, and evaporation of 3.9 mm day^{-1}. Total rainfall received during the season was 46.9 mm over 2.5 rainy days. In *kharif* 2024 (16 July-09 December), the weekly maximum and minimum temperatures ranged from 27.6-33.2 °C and 13.3-24.4 °C, respectively. Relative humidity fluctuated between 58.3-83.9%, with mean sunshine hours of 4.8 h day^{-1}, wind speed of 6.2 km hr^{-1}, and evaporation of 4.3 mm day^{-1}. Total rainfall during the crop period was 105.3 mm distributed across 5.0 rainy days. These climatic variations between the two seasons provided contrasting environments for assessing the performance of rice under different crop establishment methods and nitrogen management practices.

2.3 Layout of the Experiment and Treatment Structure

The experimental field was prepared with well-defined plots, and irrigation channels were also laid out for convenient water management. The study was conducted using a split-plot design with three replications, wherein methods of crop establishment were assigned to the main plots and nitrogen management practices to the subplots. The main plot treatments comprised three establishment methods: M_1 - transplanting, M_2 - mechanical transplanting, and M_3 - wet direct-seeded rice (WDSR). The subplot treatments included five nitrogen management practices: S_1 - 100% recommended dose of nitrogen (RDN; 120 kg N ha^{-1} applied in three splits), S_2 - Leaf Color Chart (LCC)-based nitrogen management, S_3 - 75% RDN applied as basal along with nano urea sprays (4 mL L^{-1}) at active tillering, panicle initiation, and flowering, S_4 - 100% RDN applied through slow-release (silicon-coated) urea, and S_5 - control (no nitrogen application). Uniform basal applications of phosphorus at 60 kg P_2O_5 ha^{-1}, potassium at 40 kg K_2O ha^{-1}, and farmyard manure at 10 t ha^{-1} were applied across all treatments to ensure balanced nutrient availability.

2.4 Observations Recorded

Observations on growth and yield parameters of rice were recorded at standard crop growth stages to assess the influence of the treatments. Plant height was measured from the base of the plant to the tip of the tallest leaf (or panicle at later stages) using a graduated scale, and data were recorded at 30, 60, and 90 days after sowing (DAS) and at harvest. The number of tillers per square meter was recorded by counting all tillers within a marked 1 m² area in each plot at 30, 60, and 90 DAS and at harvest to evaluate the tillering dynamics under different treatments. Dry matter accumulation was determined by sampling plants from a designated area in each plot, oven-drying the samples at 65°C to a constant weight, and converting the values to kg ha^{-1}. Dry matter was recorded at 30, 60, and 90 DAS and at harvest to quantify biomass production throughout the crop growth period.

Yield parameters were recorded at harvest. Grain yield was obtained from the net plot area, cleaned, sun-dried to 14% moisture content, and converted to kg ha^{-1}. Straw yield was determined by weighing the oven-dried above-ground biomass remaining after threshing and expressing it in kg ha^{-1}. These observations collectively provided insights into the treatment effects on the growth, development, and productivity of rice.

2.5 Statistical Analysis

All recorded data were subjected to analysis of variance (ANOVA) appropriate for the split-plot design as described by Gomez and Gomez (1984) [7]. Treatment means were compared using the critical difference (CD) at the 5% probability level, and the standard error of mean (SEm) was computed to assess variability. Seasonal analyses were performed separately for each year, and pooled analysis was conducted across years to evaluate temporal variation and the overall performance of the treatments.

3. Results and Discussion

3.1 Plant height

Plant height of rice from 30 DAS to harvest in *kharif* 2023, *kharif* 2024 and in the *kharif* pooled data showed that treatment effects appeared only after the early growth stage. At 30 DAS, plant height remained non-significant for both methods of crop establishment and nitrogen management practices across both years. However, from 60 DAS onward, significant differences were observed. Wet direct-seeded rice (M_3) and mechanical transplanting (M_2) consistently produced taller plants in *kharif* 2023, *kharif* 2024 and the pooled data, and were statistically on par, while transplanting (M_1) recorded the shortest plants. The superior performance of M_2 and M_3 may be attributed to better root establishment and stronger early vigour, enabling effective nutrient uptake during stem elongation—findings consistent with earlier reports that improved establishment techniques support vigorous vegetative growth (Selvakumar *et al.*, 2020a) [25]; (Maniraj *et al.*, 2022) [13]; (Hung *et al.*, 2024) [8].

Table 1: Plant height (cm) of *kharif* rice as influenced by methods of crop establishment and nitrogen management practices

Treatments	30 DAS			60 DAS			90 DAS			At harvest		
	Kharif			*Kharif*			*Kharif*			*Kharif*		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Methods of crop establishment (M)												
M_1: Transplanting	28.1	27.7	27.9	56	54	55	86	84	85	91	89	90
M_2: Mechanical transplanting	29.1	28.6	28.8	61	59	60	93	92	92	97	95	96
M_3: Wet direct seeded rice	29.9	29.5	29.7	63	61	62	94	93	93	98	96	97
S.Em ±	0.75	0.74	0.71	0.9	1.0	0.9	1.4	1.5	1.4	1.3	1.2	1.1
CD (P = 0.05)	NS	NS	NS	4	4	4	5	6	6	5	5	4
Nitrogen management practices (S)												
S_1: 100% RDN	29.1	28.7	28.9	62	61	62	96	94	95	99	98	99
S_2: LCC based N management	30.0	29.7	29.8	67	65	66	101	100	100	106	103	105
S_3: 75% RDN as basal + nano urea spray @ 4ml L^{-1} at active tillering, panicle initiation and flowering stages	28.9	28.4	28.6	61	60	61	94	93	94	100	97	97
S_4: 100% RDN through slow-release urea (developed by ICAR-IIRR)	30.4	30.1	30.2	68	66	67	102	101	101	107	105	106
S_5: Control	26.8	26.2	26.5	41	40	40	61	60	60	67	65	66
S.Em ±	0.98	0.91	0.92	1.3	1.1	1.1	1.6	1.5	1.5	2.0	1.6	1.6
CD (P = 0.05)	NS	NS	NS	4	3	3	5	4	4	6	5	5
Interaction												
M at S												
S.Em ±	1.70	1.58	1.60	2.2	2.0	1.9	2.7	2.7	2.6	3.4	2.7	2.8
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S at M												
S.Em ±	1.68	1.64	1.60	2.2	2.0	2.0	2.8	2.8	2.8	3.3	2.7	2.8
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Nitrogen management also significantly influenced plant height beyond 60 DAS in *kharif* 2023, *kharif* 2024 and the pooled analysis. Slow-release urea (S_4) and LCC-based nitrogen management (S_2) consistently produced the tallest plants across both years and were statistically comparable, highlighting the benefit of sustained and synchronized nitrogen release during active tillering and stem elongation. Treatments S_1 (100% RDN) and S_3 (75% RDN + nano urea sprays) recorded intermediate plant height, whereas the control (S_5) consistently produced the shortest plants in both years and in the pooled data. These results are supported by previous findings that efficient nitrogen delivery enhances vegetative growth, enzyme activity and biomass accumulation (Duttarganvi *et al.*, 2014) [6]; (Singh *et al.*, 2022) [28]; (Yadav *et al.*, 2023) [33]; (Tang *et al.*, 2025) [32]; (Mohanty *et al.*, 2020) [14]; (Namasharma *et al.*, 2023) [15].

3.2 Number of Tillers m^{-2}

The number of tillers m^{-2} of rice recorded during *kharif* 2023, *kharif* 2024, and the *kharif* pooled data (Table 2) showed that treatment effects were non-significant at 30 DAS. From 60 DAS onward, significant differences were observed among the methods of crop establishment and nitrogen management practices. Wet direct-seeded rice (M_3) and mechanical transplanting (M_2) consistently produced more tillers than transplanting (M_1), owing to better stand uniformity, minimal root disturbance, and preservation of fine root hairs that enhance early nutrient uptake and hormonal balance for tiller initiation. These results agree with earlier findings reporting superior tillering under wet direct seeding and machine transplanting (Swain *et al.*, 2013) [31]; (Pasha *et al.*, 2014) [19]; (Selvakumar *et al.*, 2020a) [25]; (Narolia *et al.*, 2020) [16].

Nitrogen management also significantly influenced tiller production from 60 DAS onward across *kharif* seasons and in the pooled data. Slow-release urea (S_4) and LCC-based N management (S_2) recorded the highest number of tillers due to synchronized nitrogen availability during active tillering. These findings align with earlier reports describing improved tillering under efficient nitrogen delivery (Duttarganvi *et al.*, 2014) [6]; (Bhavana *et al.*, 2020) [4]; (Mandal *et al.*, 2014) [12]; (Aruna *et al.*, 2023) [1]; (Bhanuprakash, 2015) [3]. Intermediate tiller numbers under S_1 and S_3 reflect adequate but less synchronized N supply, consistent with (Namasharma *et al.*, 2023) [15]; (Pedireddy *et al.*, 2024) [20]. The lowest tiller numbers under S_5 confirm nitrogen's essential role in axillary bud activation and tiller survival.

Table 2: Number of tillers m^{-2} of *kharif* rice as influenced by methods of crop establishment and nitrogen management practices

Treatments	30 DAS			60 DAS			90 DAS			At harvest		
	Kharif			*Kharif*			*Kharif*			*Kharif*		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Methods of crop establishment (M)												
M_1: Transplanting	124	122	123	329	323	326	480	470	475	471	465	468
M_2: Mechanical transplanting	124	122	123	357	351	354	526	514	520	518	508	513
M_3: Wet direct seeded rice	127	124	125	358	353	355	531	518	524	523	512	518
S.Em ±	2.3	2.9	2.0	7.1	6.4	6.5	10.5	9.7	10.1	11.7	10.6	11.0
CD (P = 0.05)	NS	NS	NS	25	25	25	41	38	40	46	42	43
Nitrogen management practices (S)												
S_1: 100% RDN	125	124	124	354	348	351	544	533	539	536	528	532
S_2: LCC based N management	129	125	127	385	380	383	591	579	585	582	572	577
S_3: 75% RDN as basal + nano urea spray @ 4ml L^{-1} at active tillering, panicle initiation and flowering stages	124	123	123	352	346	349	543	530	537	535	526	530
S_4: 100% RDN through slow-release urea (developed by ICAR-IIRR)	131	125	128	389	384	387	596	585	591	589	579	584
S_5: Control	116	115	116	257	252	255	287	276	281	278	270	274
S.Em ±	3.4	3.5	3.0	8.3	7.9	7.7	15.3	13.3	14.0	15.1	14.2	14.3
CD (P = 0.05)	NS	NS	NS	23	23	23	45	39	41	44	41	42
Interaction												
M at S												
S.Em ±	5.8	5.9	5.2	13.6	13.7	13.6	26.4	23.1	24.3	26.1	24.4	24.7
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S at M												
S.Em ±	5.7	6.1	5.0	13.8	13.8	13.8	25.8	22.8	23.9	26.1	24.7	24.7
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

3.3 Dry matter production

Dry matter production, an important indicator of crop productivity, was significantly influenced by the methods of crop establishment and nitrogen management practices from 60 DAS onward during *kharif* 2023, *kharif* 2024 and in the *kharif* pooled data (Table 3), while their interaction remained non-significant at all stages. Among the establishment methods, wet direct-seeded rice (M_3) and mechanical transplanting (M_2) consistently produced higher dry matter than transplanting (M_1). The superior dry matter accumulation under M_2 and M_3 may be attributed to uniform crop stands, uninterrupted and quicker root establishment, and higher tiller production that enhanced leaf area development and radiation interception. Preservation of fine root hairs and early root activity under M_2 and M_3 also likely supported efficient nitrogen and water uptake, thereby sustaining photosynthetic assimilation. In contrast, transplanting shock and delayed root recovery in M_1 may have temporarily reduced cytokinin transport, restricted early photosynthesis, and consequently lowered dry matter accumulation. These trends are in strong agreement with earlier reports (Swain *et al.*, 2013) [31]; (Pasha *et al.*, 2014) [19]; (Selvakumar *et al.*, 2020a) [25]; (Narolia *et al.*, 2020) [16].

Nitrogen management also played a decisive role in determining dry matter production across *kharif* seasons and the pooled data. Slow-release (silicon-coated) urea (S_4) and LCC-based nitrogen management (S_2) recorded the highest and statistically comparable dry matter production. Their superiority may be explained by sustained and synchronized nitrogen release, which maintained higher chlorophyll content, enhanced nitrate reductase activity, and supported greater cytokinin levels in roots—factors that delay senescence, prolong photosynthetic duration, and increase assimilate supply to growing tissues. These findings align with earlier studies (Duttarganvi *et al.*, 2014) [6]; (Bhavana *et al.*, 2020) [4]; (Mandal *et al.*, 2014) [12]; (Aruna *et al.*, 2023) [1]; (Bhanuprakash, 2015) [3]. Intermediate dry matter production under S_1 (100% RDN) and S_3 (75% RDN + nano urea sprays) suggests adequate but less synchronized nitrogen availability compared with S_2 and S_4. In S_1, rapid nitrogen release from conventional urea may have caused losses before plant uptake, whereas in S_3, reduced basal nitrogen combined with reliance on foliar sprays may not have ensured continuous nitrogen supply during critical growth phases. These observations agree with (Namasharma *et al.*, 2023) [15]; (Pedireddy *et al.*, 2024) [20]. The lowest dry matter production under S_5 confirms nitrogen's fundamental role in supporting photosynthesis, vegetative growth, and biomass accumulation.

Table 3: Dry matter production (kg ha^{-1}) of *kharif* rice as influenced by methods of crop establishment and nitrogen management practices

Treatments	30 DAS			60 DAS			90 DAS			At harvest		
	Kharif			*Kharif*			*Kharif*			*Kharif*		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Methods of crop establishment (M)												
M_1: Transplanting	960	945	952	5512	5366	5439	9936	9731	9833	12246	11967	12107
M_2: Mechanical transplanting	983	978	980	6169	6036	6103	11053	10885	10969	13370	13195	13282
M_3: Wet direct seeded rice	999	984	991	6250	6165	6208	11218	11024	11121	13531	13341	13436
S.Em ±	31.7	22.5	26.9	142.5	112.8	126.0	238.9	220.3	208.5	253.2	272.6	254.5
CD (P = 0.05)	NS	NS	NS	559	443	495	938	865	819	994	1070	999
Nitrogen management practices (S)												
S_1: 100% RDN	979	966	973	6616	6483	6550	11748	11562	11655	14238	13941	14089
S_2: LCC based N management	999	986	993	7048	6836	6942	12816	12530	12673	15321	15131	15226
S_3: 75% RDN as basal + nano urea spray @ 4ml L^{-1} at active tillering,	977	963	970	6518	6474	6496	11620	11467	11543	14110	13846	13978

panicle initiation and flowering stages												
S_4: 100% RDN through slow-release urea (developed by ICAR-IIRR)	1004	996	1000	7057	6926	6992	12978	12703	12840	15468	15204	15336
S_5: Control	943	933	938	2648	2559	2603	4518	4470	4494	6108	6049	6078
S.Em ±	21.6	22.7	21.2	143.7	101.5	119.9	270.9	310.4	220.1	367.6	400.8	364.0
CD (P = 0.05)	NS	NS	NS	420	296	350	791	906	642	1073	1170	1063
Interaction												
M at S												
S.Em ±	37.4	39.4	36.8	248.9	175.7	207.6	469.4	537.6	381.2	636.7	694.3	630.5
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S at M												
S.Em ±	65.6	48.4	56.3	305.9	238.9	268.6	483.0	528.9	399.7	623.2	678.2	618.7
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 4: Grain yield (kg ha^{-1}), straw yield (kg ha^{-1}) and harvest index (%) of *kharif* rice as influenced by methods of crop establishment and nitrogen management practices

Treatments	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})			Harvest index (%)		
	Kharif			***Kharif***			***Kharif***		
	2023	**2024**	**Pooled**	**2023**	**2024**	**Pooled**	**2023**	**2024**	**Pooled**
Methods of crop establishment (M)									
M_1: Transplanting	5350	5251	5300	6596	6483	6540	44.6	44.7	44.7
M_2: Mechanical transplanting	5998	5923	5961	7065	6972	7018	45.7	45.8	45.7
M_3: Wet direct seeded rice	6091	6010	6051	7137	7024	7081	45.8	45.9	45.8
S.Em ±	135.4	154.1	142.7	107.4	98.3	90.5	1.10	1.13	0.89
CD (P = 0.05)	532	605	560	422	386	356	NS	NS	NS
Nitrogen management practices (S)									
S_1: 100% RDN	6311	6226	6268	7627	7526	7577	45.3	45.3	45.3
S_2: LCC based N management	6933	6793	6863	8072	7927	7999	46.2	46.1	46.1
S_3: 75% RDN as basal + nano urea spray @ 4ml L^{-1} at active tillering, panicle initiation and flowering stages	6213	6162	6188	7596	7495	7546	45.0	45.10	45.0
S_4: 100% RDN through slow-release urea (developed by ICAR-IIRR)	7053	6913	6983	8114	7980	8047	46.5	46.4	46.4
S_5: Control	2554	2547	2550	3254	3203	3228	43.9	44.3	44.1
S.Em ±	169.4	149.2	147.7	137.4	131.6	134.2	1.16	0.93	1.03
CD (P = 0.05)	494	436	431	401	384	392	NS	NS	NS
Interaction									
M at S									
S.Em ±	293.3	258.4	255.8	238.1	227.9	232.3	2.01	1.60	1.79
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS
S at M									
S.Em ±	295.2	277.8	269.7	238.5	226.3	226.7	2.10	1.82	1.83
CD (P = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS

3.4 Yield

3.4.1 Grain Yield

The grain yield of rice during *kharif* 2023, *kharif* 2024, and in the *kharif* pooled data (Table 4) was significantly influenced by the methods of crop establishment and nitrogen management practices, while their interaction remained non-significant. Among establishment methods, wet direct-seeded rice (M_3) recorded the highest grain yield, which was statistically on par with mechanical transplanting (M_2), whereas transplanting (M_1) consistently produced the lowest yield. The superior performance of M_3 and M_2 may be attributed to rapid, uniform crop establishment, uninterrupted early root growth, enhanced root-soil contact, and reduced transplanting shock, all of which favour greater tiller survival, improved nutrient uptake, and efficient assimilate translocation. These observations are consistent with earlier reports (Padma *et al.*, 2023) [18]; (Kumar *et al.*, 2023) [9]; (Ravindranath and Jaidev, 2018) [23].

Nitrogen management also exerted a significant influence on grain yield. Slow-release (silicon-coated) urea (S_4) produced the highest yield and was on par with LCC-based nitrogen management (S_2), attributable to their ability to synchronize nitrogen supply with crop demand, thereby sustaining leaf area duration, improving photosynthetic efficiency, and enhancing spikelet fertility. Similar findings were reported by (Prasad *et al.*, 2013) [21]; (Nayak *et al.*, 2017) [17]; (Singh *et al.*, 2020) [27]; (Aruna *et al.*, 2023) [1]. Intermediate yields under S_1 (100% RDN) and S_3 (75% RDN + nano urea sprays) indicate adequate but less synchronized nitrogen availability compared with S_2 and S_4. Although nano urea enhanced foliar uptake, it could not fully replace the need for a continuous soil-N supply. Comparable results were documented earlier (Pedireddy *et al.*, 2024) [20]; (Sharma *et al.*, 2023) [26]. The lowest grain yield under S_5 reflects the limiting effect of nitrogen deficiency on tiller survival, spikelet formation, and grain filling.

3.4.2 Straw Yield

Straw yield during *kharif* 2023, *kharif* 2024, and the pooled *kharif* data (Table 4) was significantly influenced by the methods of crop establishment and nitrogen management practices, while the interaction remained non-significant. Wet direct-seeded rice (M_3) and mechanical transplanting (M_2) recorded significantly higher straw yields and were statistically on par, whereas transplanting (M_1) produced the lowest values. The higher straw yield under M_3 and M_2 may be attributed to better crop stand establishment, uninterrupted early root growth, superior tiller production, and enhanced dry matter partitioning toward vegetative biomass—advantages not fully realized under M_1 due to transplanting shock and delayed root recovery. These findings align with earlier reports (Padma *et al.*, 2023) [18]; (Kumar *et al.*, 2023) [9]; (Ravindranath and Jaidev, 2018) [23].

Nitrogen management showed clear differences in straw yield. Slow-release urea (S_4) produced the highest straw yield and was statistically comparable with LCC-based nitrogen management (S_2), both of which were superior to S_1 and S_3. Their effectiveness is attributed to sustained nitrogen release, prolonged leaf area duration, delayed senescence, and enhanced vegetative vigour. These results are supported by earlier findings (Prasad *et al.*, 2013) [21]; (Nayak *et al.*, 2017) [17]; (Singh *et al.*, 2020) [27]; (Aruna *et al.*, 2023) [1]. Intermediate straw yields observed under S_1 and S_3 further indicate that continuous nitrogen availability—not merely nitrogen quantity—is essential for maximizing biomass accumulation. The lowest straw yield under S_5 was due to severe nitrogen deficiency limiting vegetative growth and dry matter production.

3.4.3 Harvest Index (%)

The harvest index (HI) of rice during *kharif* 2023, *kharif* 2024 and in the *kharif* pooled data (Table 4) was not significantly affected by either the methods of crop establishment or nitrogen management practices, and their interaction remained non-significant. Although grain and straw yields varied significantly among treatments, the proportional increase in grain and biomass remained nearly parallel, resulting in non-significant differences in HI. This indicates that establishment methods and nitrogen management influenced total biomass production rather than altering assimilate partitioning efficiency between grain and straw. The stable HI across treatments suggests its strong genetic control, with agronomic practices exerting minimal influence on the grain-to-biomass ratio. Similar observations were previously reported (Mahajan *et al.*, 2013) [11]; (Rana and Verma, 2018) [22].

4. Conclusion

Overall, *kharif* results across both years and the pooled data showed that crop establishment and nitrogen management significantly influenced rice performance from 60 DAS onward. Wet direct-seeded rice (M_3) and mechanical transplanting (M_2) consistently outperformed transplanting (M_1) in plant height, tillering, dry matter production, grain yield and straw yield due to better early establishment and efficient nutrient uptake. Among nitrogen practices, slow-release urea (S_4) and LCC-based management (S_2) proved most effective, while S_1 and S_3 produced moderate responses and the control (S_5) remained lowest. Harvest index was unaffected, reflecting strong genetic regulation of assimilate partitioning. Overall, the combination of M_3 or M_2 with S_4 or S_2 emerges as a productive and sustainable strategy for improving *kharif* rice performance**.**

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