



RESEARCH ARTICLE

Influence of rice straw incorporation and nitrogen levels on growth dynamics, productivity and growth-yield relationships of rice cv. MTU1010

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Received: 02 June 2026; Accepted: 15 July 2026; Available online: Version 1.0: 01 August 2026

Cite this article: Majumder M, Shankar T, Sarkar S, Reddy MD, Dash B, Boddana P. Influence of rice straw incorporation and nitrogen levels on growth dynamics, productivity and growth-yield relationships of rice cv. MTU1010. Plant Science Today. 2026; 13(sp5): 1-11. <https://doi.org/10.14719/pst.15806>

Abstract

Sustainable management of rice straw through *in situ* incorporation has emerged as an important strategy for improving soil health and minimising residue burning in rice-based cropping systems. Therefore, optimisation of nitrogen (N) application under rice straw (RS) incorporation is essential for improving crop growth, productivity and efficient utilisation of available nutrients. The influence of three levels of RS incorporation (0, 3 and 6 megagram (Mg) ha⁻¹) and four levels of fertiliser-N (0, 40, 80 and 120 kg N ha⁻¹) application on growth dynamics and rice yield was evaluated. Results revealed that moderate straw incorporation (S₃) significantly ($p < 0.05$) improved plant height, total tillers per square metre, leaf area index (LAI), grain yield and straw yield compared with S₀. Application of 120 kg N ha⁻¹ resulted in the highest growth attributes and grain yields of 4.9 and 5.1 Mg ha⁻¹ during 2024 and 2025 respectively. Grain yield under S₃ increased by 7.9 and 7.5 % over S₀ and by 13.9 and 16.2 % over S₆ during 2024 and 2025 respectively. Regression analysis indicated strong positive relationships between grain yield and growth parameters, particularly total tillers per square metre and LAI at later crop growth stages. The study concluded that incorporation of rice straw at the rate of 3 Mg ha⁻¹ along with the application of 120 kg N ha⁻¹ enhanced crop productivity while reducing environmental pollution associated with open-field rice straw burning in eastern India, contributing to SDG 2 (Zero Hunger), SDG 13 (Climate Action) and SDG 15 (Life on Land).

Keywords: carbon sequestration; crop residue incorporation; greenhouse gas emission; rice yield

Introduction

Rice (*Oryza sativa* L.) contributes nearly 21 % of the total global calorie intake and occupies around 11 % of the total cultivated area worldwide (1–3). In India, rice is the principal food crop cultivated predominantly during the rainy (kharif) season and plays a crucial role in food and nutritional security. During 2024–25, rice was cultivated over an area of about 51.30 million hectares with a total production of nearly 150.2 million tonnes in the country (4). Odisha ranked sixth in rice production during 2024–25, covering approximately 3.8 million hectares with a production of 9.5 million tonnes of rice (5). However, the average productivity of rice in Odisha (2485 kg ha⁻¹) remains lower than the national average productivity of 2929 kg ha⁻¹ (5). The productivity scenario becomes more critical in the southern districts of Odisha such as Gajapati, where rice productivity is reported to be only about 1770 kg ha⁻¹ (6). The dominance of coarse textured, low fertile soil, coupled with poor organic carbon decreased the rice productivity rice in the region (7).

In recent years, mechanised harvesting of rice generates huge amounts of left over stubble (30–40 cm height) in the field (8). Like the farmers of northern India, farmers of this region also burn the left-over stubble. This causes the generation of huge amount of carbon dioxide and losses of plant nutrients (9, 10). Such activity pollutes the environment and deteriorates soil health by hampering the microbial activities involved in nutrient cycling (11, 12). Rice straw contains around 40 % of nitrogen (N), 30–35 % of phosphorus (P), 80–85 % of potassium (K) and 40–50 % of sulphur (13). Thus, incorporating rice straw can substantially improve the soil fertility level and sustain crop productivity. Long-term incorporation of rice residue has also been reported to improve soil organic matter accumulation, enhance soil enzymatic activity and increase N use efficiency (14–16).

Sequestration of carbon (C) improves the hydro-physical environment of soil and thus reduces nutrient losses through leaching. Enrichment of soil carbon may create opportunities for C

credit and climate-smart agricultural initiatives for farmers. Rice straw possesses a wide C : N (80 : 1) ratio. Therefore, sole incorporation of rice straw initiates the microbial driven process of immobilisation and reduces the availability of mineral N. To shorten the duration of the immobilisation period, application of inorganic N to the soil is a common practice (17, 18). However, the amount of inorganic N that has to be applied against a known amount of incorporated straw has to be standardised on the basis of soil and climate type.

Nitrogen, being a major constituent of chlorophyll, proteins and nucleic acids influences various plant metabolic and physiological processes and regulates plant growth. Adequate N supply promotes leaf area development, tillering, biomass accumulation, grain formation in rice. The synchronisation between N release from incorporated straw and crop N demand therefore becomes highly important for sustaining crop growth and yield (19). Several studies have indicated that combined application of rice straw and appropriate N levels can improve nutrient dynamics and soil health (15, 20, 21). Integrated approach of rice straw incorporation with application of fertiliser N, significantly enhanced grain yield, soil N pools, N use efficiency and soil enzymatic activities in rice-based cropping systems (21). Similarly, long-term straw incorporation has been shown to improve N mineralisation and nutrient availability through enhanced microbial biomass and biological activity.

Although considerable research has been conducted on crop residue management in rice-wheat sequence in well fertile soils of Indo-Gangetic Plain of India, scant information is available in a contrast agro-ecological environment of Southern Odisha with rice-rice cropping system. Therefore, the present study was undertaken to evaluate the interactive effects of varying levels of rice straw incorporation and N fertilisation on growth, productivity and growth-yield relationships of rice under the sub-humid agro-climatic condition of southern Odisha.

Materials and Methods

Study site and soil

A field study was conducted during the rainy (kharif) seasons of 2024 and 2025 at the Postgraduate Research Farm of the

M S Swaminathan School of Agriculture, Centurion University of Technology and Management, located in the Gajapati district of Odisha, India. The experimental site is geographically situated at 18.8043° N latitude and 84.1787° E longitude with an altitude of approximately 90 m above mean sea level. The region falls under the sub-humid climatic zone with an aridity index of 0.63. The experimental soil belonged to the order Rhodic Paleustalfs with sandy loam texture. It was slightly acidic in reaction (pH 6.3), non-saline (EC 0.47 dS m⁻¹), low in organic carbon (0.45 %), low in available N (177 kg ha⁻¹) and medium in available P (13 kg ha⁻¹) and available K (160 kg ha⁻¹).

Meteorological conditions

The weather conditions prevailing during the crop growth period differed slightly between the two experimental years and are presented in Fig. 1 and 2. During the growing period of 2024 and 2025, the crop received total rainfall of 656.5 and 681.8 mm respectively. The weekly distribution of rainfall is presented in Fig. 1. The highest rainfall was recorded during the 33rd standard meteorological week (SMW) in 2024 (179.6 mm), while in 2025 the maximum rainfall occurred during the 43rd SMW (113.5 mm). Mean relative humidity during the crop season ranged from 73.2–84.3 % in 2024 and from 73.7–81.4 % in 2025. Bright sunshine hours (BSS) varied from 5.98–8.89 hr day⁻¹ during 2024 and from 5.6–9.2 hr day⁻¹ during 2025 (Fig. 2). The mean weekly temperature ranged between 26.8 °C and 29.7 °C during 2024 and between 26.1 °C and 30.1 °C during 2025. Both relative humidity and temperature exhibited a declining trend during the latter part of the crop growth period. Fig. 1 shows that in some phases, the crop received less rainfall, this was compensated by supplemental irrigation as per the crop requirement (Table 1).

Table 1. Details of life saving irrigation during the crop growing period

Season	0–30 DAT (32–35 SMW)	31–60 DAT (35–39 SMW)	61–90 DAT (40–45 SMW)	Total
	Irrigation (mm)			
2024	150	100	150	400
2025	150	50	100	300

DAT: days after transplanting; SMW: standard meteorological week.

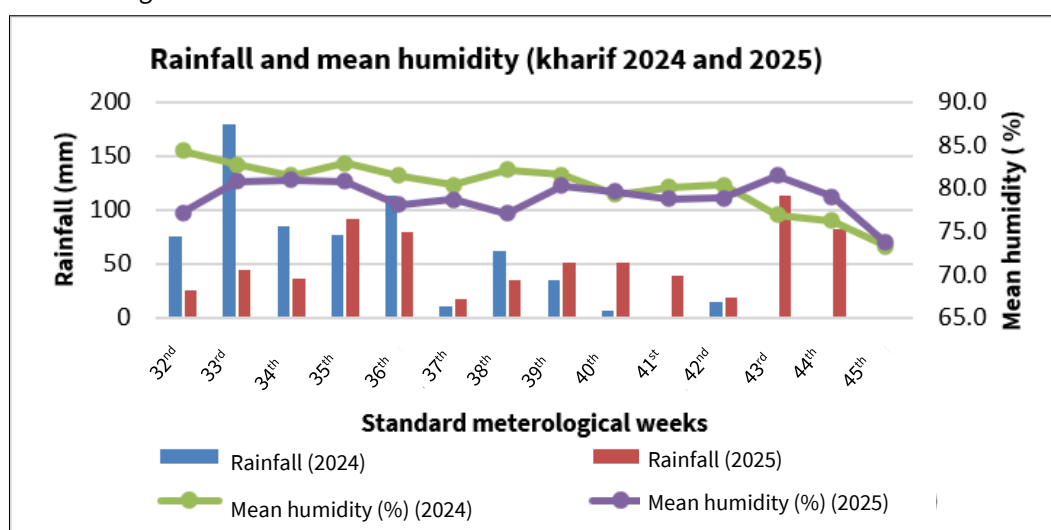


Fig. 1. Temporal status of rainfall (weekly total) and relative humidity (weekly mean) during the crop growing period (kharif 2024 and 2025).

Source: Meteorological observatory of the M S Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha.

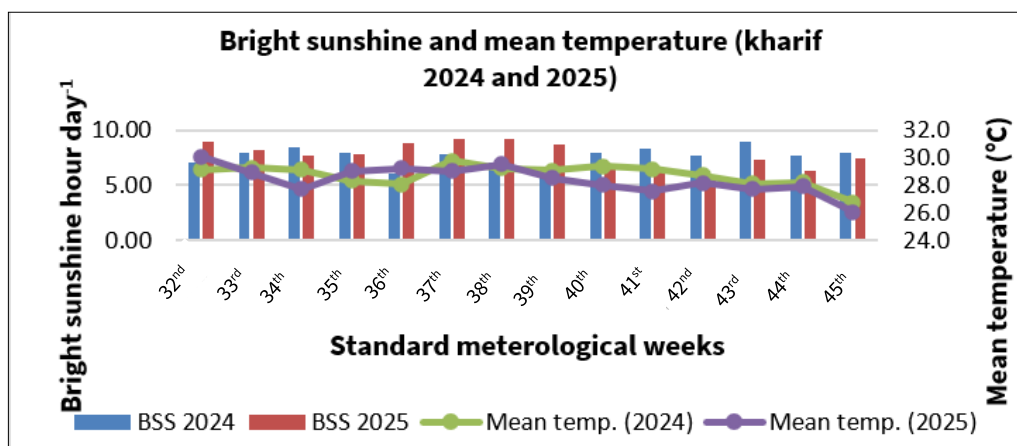


Fig. 2. Temporal status of bright sunshine hour (weekly mean) and atmospheric temperature (weekly mean) during the crop growing period (kharif 2024 and 2025).

Source: Meteorological observatory of the M S Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha.

Experimental design and treatments

A split-plot design with 3 replications was used to set up the experiment, comprising three rice straw incorporation levels, viz., S_0 (0 Mg ha⁻¹), S_3 (3 Mg ha⁻¹) and S_6 (6 Mg ha⁻¹) in the main plots and four N levels, viz., N_0 (0 kg N ha⁻¹), N_{40} (40 kg N ha⁻¹), N_{80} (80 kg N ha⁻¹) and N_{120} (120 kg N ha⁻¹) in the subplots. The gross plot size was 5.0 × 4.2 m. Rice residue at the specified rates was chopped by using a rice straw chopper and incorporated into the soil up to a depth of 10–15 cm with the help of a power tiller. Straw incorporation was carried out 25 days before transplanting, followed by submergence for proper decomposition of the rice straw.

Crop establishment and management

The nursery was raised using a seed rate of 30–35 kg ha⁻¹ with uniform broadcasting in a well-prepared seedbed. Twenty-five-day-old seedlings of rice variety MTU1010 were transplanted on 8 August, 2024 and 2 August, 2025 respectively, with a spacing of 20 cm (plant to plant) × 15 cm (row to row). The crop was harvested on November 6, 2024 and November 4, 2025. Nitrogen, P and K were supplied through urea, single superphosphate (SSP) and muriate of potash (MOP) respectively. Phosphorus and K were applied uniformly at 40 and 40 kg ha⁻¹ respectively, while N was applied according to treatment levels (0, 40, 80 and 120 kg N ha⁻¹). Nitrogen was applied in three splits, with 50 % as basal, 25 % at active tillering (AT) and the remaining 25 % at panicle initiation (PI) stage. Full doses of P and K were applied as basal during the final land preparation. All recommended agronomic and plant protection practices were followed uniformly for all treatments.

Observations recorded

Observations on growth parameters such as plant height, total tillers per square metre and leaf area index (LAI) were recorded at 30, 60 and 90 days after transplanting (DAT) following the standard procedures (22). The LAI was computed as the ratio of total leaf area to the corresponding ground area occupied by the crop following the method of Watson (23). Grain and straw yield were recorded at harvest and expressed in megagrams per hectare (Mg ha⁻¹) which is equivalent to tonnes per hectare. Harvest index (HI) was calculated as per standard procedure (24).

Statistical analysis

The experimental data collected for different parameters were subjected to statistical analysis appropriate for a split-plot design using analysis of variance (ANOVA) in R software version 4.2.3. The

significance of treatment effects was tested through the *F*-test at 5 % probability level. Whenever the treatment effects were found to be significant, the least significant difference (LSD) values were calculated for comparison of treatment means following the procedure described by statistical procedures for agricultural research (25).

Results and Discussion

Influence of rice straw incorporation and nitrogen levels on growth parameters

Rice straw incorporation and N levels significantly influenced most growth parameters at different crop growth stages during both years of study (Table 2).

Rice straw incorporation significantly influenced plant height at all growth stages during both years of the study. Plant height increased progressively from 30 to 90 DAT under all treatments. At 30 DAT, S_0 recorded the highest plant height of 44.4 and 44.2 cm during 2024 and 2025 respectively, which was 9.1 and 10.2 % higher than S_6 . The treatment S_3 recorded intermediate values at this stage. At 60 DAT, S_0 recorded the tallest plants during 2024 (79.5 cm), which remained statistically at par with S_3 (78.4 cm). During 2025, S_3 recorded the highest plant height (80.6 cm), which was 6.5 % higher than S_6 . At 90 DAT, S_3 recorded the maximum plant height of 94.4 and 95.8 cm during 2024 and 2025 respectively. During 2024, S_3 remained statistically at par with S_0 (89.9 cm), whereas during 2025 it was significantly superior to the remaining treatments. Compared to S_6 , under S_3 plant height increased at 90 DAT by 6.7 and 7.9 % during 2024 and 2025 respectively. The lowest plant height throughout the crop growth period was recorded under S_6 . The variation in plant height under different rice straw incorporation levels might be due to differences in nutrient availability and straw decomposition dynamics during crop growth. The higher plant height under S_0 at the early growth stage could be attributed to immediate nitrogen availability in the absence of straw-induced immobilisation, whereas incorporation of higher straw quantity under S_6 might have temporarily restricted N availability due to its wider C : N ratio (26). However, at later growth stages, S_3 produced taller plants, which might be associated with gradual decomposition of straw and subsequent nutrient release, leading to improved nutrient uptake and crop vigour (27–29). Moderate straw incorporation may also have improved soil physical and biological conditions, thereby supporting better plant growth.

Table 2. Influence of rice straw incorporation and nitrogen levels on growth parameters

Treatments	Plant height (cm)						Total tillers per square metre						Leaf area index					
							Days after transplanting (DAT)											
	30 DAT		60 DAT		90 DAT		30 DAT		60 DAT		90 DAT		30 DAT		60 DAT		90 DAT	
	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025	2024	2025
Rice straw incorporation																		
S₀	44.4	44.2	79.5	78.9	89.9	89.8	158.7	160.9	264.6	267.1	258.2	260.7	1.63	1.63	4.50	4.44	3.07	3.17
S₃	42.2	41.8	78.4	80.6	94.4	95.8	152.3	154.7	265.3	272.4	262.0	266.1	1.49	1.57	4.35	4.67	3.20	3.36
S₆	40.7	40.1	75.5	75.7	88.5	88.8	144.4	145.9	260.0	263.2	254.4	257.6	1.36	1.41	4.18	4.33	3.02	3.10
S. Em. (±)	0.13	0.49	0.43	0.41	1.14	0.83	0.64	0.79	2.23	0.95	2.02	0.86	0.01	0.02	0.04	0.03	0.03	0.03
LSD (p = 0.05)	0.5	1.9	1.7	1.6	4.5	3.3	2.5	3.1	NS	3.7	NS	3.4	0.04	0.08	0.16	0.11	0.11	0.13
Nitrogen levels																		
N₀	39.8	39.9	72.6	73.1	79.5	79.6	138.1	139.9	252.0	254.7	247.1	249.6	1.31	1.31	3.89	3.98	2.64	2.76
N₄₀	41.2	40.6	75.6	76.4	86.4	87.2	145.0	147.3	258.4	262.0	254.1	257.2	1.42	1.45	4.18	4.32	3.01	3.10
N₈₀	43.4	42.7	79.9	80.5	95.2	95.8	156.2	158.9	267.3	272.6	262.2	265.9	1.54	1.61	4.51	4.71	3.25	3.37
N₁₂₀	45.4	44.8	83.0	83.5	102.7	103.2	167.9	169.2	275.7	281.0	269.4	273.3	1.69	1.78	4.78	4.90	3.48	3.61
S. Em. (±)	0.16	0.56	0.42	0.47	0.73	0.88	0.93	0.59	1.34	0.65	1.19	0.86	0.02	0.02	0.03	0.06	0.03	0.03
LSD (p = 0.05)	0.5	1.7	1.3	1.4	2.2	2.6	2.8	1.8	4.0	1.9	3.5	2.5	0.05	0.05	0.10	0.18	0.08	0.10
Rice straw incorporation × Nitrogen levels																		
S. Em. (±)	0.28	0.97	0.73	0.82	1.26	1.52	1.62	1.02	2.32	1.13	2.07	1.48	0.03	0.03	0.06	0.11	0.04	0.06
LSD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

LSD (p = 0.05): Least significant difference at 5 % probability level; NS: non-significant.

Irrespective of crop stage, a significant increase in plant height was noticed with each increment of 40 kg N ha⁻¹ from N₀ to N₁₂₀. Compared to N₀, plant height under N₁₂₀ increased by 14.0 and 12.3 % at 30 DAT, 14.3 and 14.2 % at 60 DAT and 29.2 and 29.6 % at 90 DAT during 2024 and 2025 respectively. Further, N₁₂₀ improved plant height over N₈₀ by 4.6 and 4.9 % at 90 DAT during 2024 and 2025 respectively. The lowest plant height was consistently observed under N₀ throughout the crop growth period. Overall, plant height increased steadily with crop age and higher N application. Nitrogen promotes cell division, cell elongation, chlorophyll synthesis, thereby enhancing plant height. Nitrogen being a major constituent of proteins and nucleic acids could have improved photosynthetic activity, resulting in taller plants under N₁₂₀ throughout the crop growth period (30, 31). Slightly higher plant height at later growth stages during 2025 over 2024 might also be associated with a comparatively less water-stressed environment, particularly better distribution of rainfall and suitable humidity during the active growth period, which possibly supported improved nutrient uptake and crop growth (Fig. 1).

The interaction effect between rice straw incorporation and N levels on plant height was found to be non-significant at all growth stages during both years of study.

Rice straw incorporation significantly influenced total tillers per square metre at 30 DAT during both the years and at 60 and 90 DAT during 2025. Irrespective of treatments, tiller production increased up to 60 DAT and declined slightly at 90 DAT. During the initial stage, S₀ recorded the highest tiller count of 158.7 and 160.9 m² during 2024 and 2025 respectively, which was 9.9 and 10.3 % higher than S₆. However, at later stages, S₃ recorded the maximum tiller count with the values of 265.3 and 272.4 m² at 60 DAT and 262.0 and 266.1 m² at 90 DAT during 2024 and 2025 respectively. During 2025, S₃ increased tiller count over S₆ by 3.5 % at 60 DAT and 3.3 % at 90 DAT, while the corresponding increase over S₀ was 2.0 and 2.1 % respectively. The lowest tiller population throughout the crop growth period was observed under S₆. The

comparatively higher tiller count under S₀ at the initial stage could be due to immediate nutrient availability, whereas the improved tiller production under S₃ at later stages might be attributed to gradual decomposition of incorporated straw and synchronised nutrient release during active tillering. Moderate straw incorporation may also have improved microbial activity, thereby favouring better tiller development. In contrast, comparatively lower tiller population under S₆ could be due to temporary nutrient immobilisation caused by higher straw load (21, 32). The slight decline in tiller number from 60 to 90 DAT may be attributed to the mortality of non-productive tillers during crop maturation.

Nitrogen application significantly increased total tillers per square metre at all growth stages during both years of study. The number of tillers increased progressively with increasing N levels from N₀–N₁₂₀. The treatment N₁₂₀ consistently recorded the highest tiller count at all stages with values of 167.9 and 169.2 m² at 30 DAT, 275.7 and 281.0 m² at 60 DAT and 269.4 and 273.3 m² at 90 DAT during 2024 and 2025 respectively. Compared to N₀, N₁₂₀ increased tiller count by 21.6 and 20.9 % at 30 DAT, 9.4 and 10.3 % at 60 DAT and 9.0 and 9.5 % at 90 DAT during 2024 and 2025 respectively. Similarly, N₁₂₀ recorded 7.5 and 6.5 % higher tillers than N₈₀ at 30 DAT, 3.2 and 3.1 % at 60 DAT and 2.7 and 2.8 % at 90 DAT during 2024 and 2025 respectively. The lowest tiller population throughout the crop growth period was observed under N₀. Nitrogen promoted cell division, meristematic activity and rapid vegetative growth of rice and adequate N supply under N₁₂₀ possibly enhanced photosynthetic activity and carbohydrate production, thereby supporting the formation and survival of more tillers throughout the crop growth period (33). Lower tiller number under N₀ could be due to N deficiency, which restricted vegetative growth and tiller initiation.

The interaction effect between rice straw incorporation and N levels on total tillers per square metre was found to be non-significant at all growth stages during both years of study.

Rice straw incorporation significantly influenced LAI at all stages of crop growth. Irrespective of treatments, LAI increased up to 60 DAT and declined thereafter at 90 DAT due to active leaf development during vegetative growth and subsequent leaf senescence at later stages. At 30 DAT, S_0 recorded the highest LAI of 1.63 during both years. However, during 2025 it remained statistically at par with S_3 (1.57). Compared with S_6 , S_0 increased LAI by 19.9 and 15.6 % during 2024 and 2025 respectively. At 60 DAT, S_0 recorded the highest LAI during 2024 (4.50), which remained statistically at par with S_3 (4.35), whereas during 2025, S_3 recorded the maximum LAI (4.67). Compared with S_6 , S_3 increased LAI by 4.1 and 7.9 % during 2024 and 2025 respectively. At 90 DAT, the highest value was recorded with S_3 in both the years of study, which was followed by S_0 and the lowest value was recorded in S_6 . The higher LAI observed under S_0 during the initial stage and under S_3 at 60 DAT indicates that moderate straw incorporation created a favourable environment for canopy development during the active vegetative phase. Incorporation of 3 Mg ha⁻¹ straw possibly ensured better synchronisation of nutrient release with crop demand, resulting in improved leaf expansion and photosynthetic area. Similar results have been reported previously (34–36).

Nitrogen application significantly increased LAI at all growth stages during both years of the study. The LAI increased progressively with increasing N levels from N_0 to N_{120} . The treatment N_{120} consistently recorded the highest LAI at all stages with values of 1.69 and 1.78 at 30 DAT, 4.78 and 4.90 at 60 DAT and 3.48 and 3.61 at 90 DAT during 2024 and 2025 respectively. Compared to N_0 , N_{120} increased LAI by 29.0 and 35.9 % at 30 DAT, 22.9 and 23.1 % at 60 DAT and 31.8 and 30.8 % at 90 DAT during 2024 and 2025 respectively. Similarly, N_{120} recorded 9.7 and 10.6 % higher LAI than N_{80} at 30 DAT, 6.0 and 4.0 % at 60 DAT and 7.1 and 7.1 % at 90 DAT during 2024 and 2025 respectively. The lowest LAI throughout the crop growth period was recorded under N_0 . The progressive increase in LAI with increasing nitrogen levels might be due to more leaf production, chlorophyll formation and canopy expansion under adequate N supply (37). Higher N availability under N_{120} possibly promoted vigorous vegetative growth and greater photosynthetic surface area, resulting in higher LAI throughout the crop growth period compared to N_0 which was restricted to leaf growth under N deficiency (34).

The interaction effect between rice straw incorporation and nitrogen levels on LAI was non-significant at all growth stages during both years.

Influence of rice straw incorporation and nitrogen levels on yield

Rice straw incorporation and N levels significantly influenced grain yield, straw yield and HI during both years of study (Table 3).

The grain yield of rice was significantly influenced by rice straw incorporation during both years of the study. Incorporation of 3 Mg ha⁻¹ straw (S_3) recorded the highest grain yield of 4.1 and 4.3 Mg ha⁻¹ during 2024 and 2025 respectively, which was statistically at par with S_0 during 2025. The increase in grain yield under S_3 over S_6 was about 13.9 and 16.2 % during 2024 and 2025 respectively. Application of higher straw level (S_6) resulted in comparatively lower grain yield, recording 3.6 and 3.7 Mg ha⁻¹ during 2024 and 2025 respectively. Across the treatments, grain yield was slightly higher during 2025 compared to 2024. The higher grain yield under S_3 might be attributed to improved synchronisation of nutrient release with crop demand following gradual decomposition of incorporated straw. Moderate straw incorporation possibly enhanced soil moisture retention, microbial activity and nutrient availability, which collectively supported better crop growth, tillering and canopy development, resulting in higher assimilate production and grain formation (38). In contrast, the comparatively lower grain yield under S_6 could be due to temporary N immobilisation caused by the higher quantity of straw with wider C : N ratio, which may have restricted nutrient availability during critical growth stages. Slightly higher grain yield during 2025 might also be associated with comparatively favourable rainfall distribution during the reproductive phase, along with suitable temperature and humidity conditions, which possibly supported better nutrient mineralisation, sustained photosynthetic activity and improved grain filling. Similar findings have also been reported by earlier researchers (20, 14).

Nitrogen application significantly improved grain yield during both years of study. Grain yield increased progressively with increasing N levels from N_0 to N_{120} . During 2024, application of 40, 80 and 120 kg N ha⁻¹ increased grain yield by 50.0, 83.3 and 104.2 % respectively, over N_0 , whereas during 2025 the corresponding increase was 54.2, 95.8 and 112.5 % respectively. The treatment N_{120} recorded the highest grain yield of 4.9 and 5.1 Mg ha⁻¹ during 2024 and 2025 respectively, followed by N_{80} with 4.4 and 4.7 Mg ha⁻¹. Further, N_{120} improved grain yield by 11.4 and 8.5 % over N_{80} during 2024 and 2025 respectively and by more than two-fold over N_0 during both years of the study. The lowest grain yield was recorded

Table 3. Influence of rice straw incorporation and nitrogen levels on yield

Treatments	Grain yield (Mg ha ⁻¹)		Straw yield (Mg ha ⁻¹)		Harvest index (%)	
	2024	2025	2024	2025	2024	2025
Rice straw incorporation						
S_0	3.8	4.0	4.4	4.6	46.0	46.2
S_3	4.1	4.3	4.7	4.9	46.1	46.1
S_6	3.6	3.7	4.2	4.3	46.1	46.0
S. Em. (±)	0.09	0.06	0.06	0.12	0.51	0.86
LSD ($p = 0.05$)	0.3	0.3	0.2	0.5	NS	NS
Nitrogen levels						
N_0	2.4	2.4	3.1	3.2	43.3	43.1
N_{40}	3.6	3.7	4.1	4.3	46.8	46.7
N_{80}	4.4	4.7	4.9	5.1	47.4	47.8
N_{120}	4.9	5.1	5.6	5.8	46.8	46.7
S. Em. (±)	0.04	0.07	0.11	0.07	0.68	0.72
LSD ($p = 0.05$)	0.1	0.2	0.3	0.2	2.0	2.1
Rice straw incorporation × Nitrogen levels						
S. Em. (±)	0.08	0.12	0.19	0.12	1.18	1.24
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS

LSD ($p = 0.05$): Least significant difference at 5 % probability level; NS: non-significant.

under N_0 with 2.4 Mg ha^{-1} in both years. Overall, grain yield was comparatively higher during 2025 than 2024 across all N levels. Higher grain yield under increasing N levels could be associated with improved source-sink relationship and efficient utilisation of growth resources by the crop (36). Application of higher N doses, particularly N_{120} , possibly maintained a healthier and more active canopy for a longer duration, which enhanced dry matter accumulation and partitioning towards grains. Improved yield under N_{120} over N_{80} was also supported by greater tiller production and higher LAI observed during the study under low fertile sandy loam soils (21).

The interaction effect between rice straw incorporation and N levels on grain yield was found to be non-significant during both years.

Straw yield was significantly affected by rice straw incorporation during both years. The treatment S_3 recorded the highest straw yield of 4.7 and 4.9 Mg ha^{-1} during 2024 and 2025 respectively, which was statistically at par with S_0 during 2025. Incorporation of 3 Mg ha^{-1} straw increased straw yield by 11.9 and 14.0 % over S_6 during 2024 and 2025 respectively. The lowest straw yield was recorded under S_6 with values of 4.2 and 4.3 Mg ha^{-1} during the respective years. Similar to grain yield, straw yield was comparatively higher during 2025 across all treatments (21).

Nitrogen levels had a significant influence on straw yield during both years. Straw yield increased steadily with successive increases in N application from N_0 to N_{120} . The highest straw yield was recorded under N_{120} with 5.6 and 5.8 Mg ha^{-1} during 2024 and 2025 respectively and it remained significantly different from all other treatments. The increase in straw yield under N_{120} over N_0 was 80.6 % during 2024 and 81.3 % during 2025. The lowest straw yield was observed under N_0 with 3.1 and 3.2 Mg ha^{-1} during the respective years. Similar findings were previously reported (39).

The interaction effect between rice straw incorporation and N levels on straw yield was found to be non-significant during both years.

Rice straw incorporation did not have any significant effect on HI during either year of study. Harvest index values remained almost similar across all straw incorporation treatments, ranging from 46.0–46.1 % during 2024 and from 46.0–46.2 % during 2025.

Nitrogen levels significantly influenced HI during both years. Application of N up to N_{80} improved HI, after which no further improvement was observed. The highest HI was recorded under N_{80} (47.4 and 47.8 % during 2024 and 2025 respectively), which remained statistically at par with N_{40} and N_{120} . In contrast, the lowest HI was observed under N_0 with values of 43.3 and 43.1 % during 2024 and 2025 respectively. The higher HI under N_{80} might be due to better partitioning of assimilates towards grain yield under adequate N supply. In contrast, lower HI under N_0 could be associated with poor crop growth and reduced grain formation under N deficiency.

The interaction effect between rice straw incorporation and N levels on HI was non-significant during both years.

Relationship of grain yield with growth parameters at different crop stages under varying levels of straw incorporation and nitrogen levels

Regression analysis revealed a positive relationship between grain yield and growth parameters at different crop growth stages under varying levels of straw incorporation (Fig. 3). The relationship between plant height and grain yield strengthened with advancement of crop

growth stage, as indicated by the increase in coefficient of determination (R^2) values from 0.0865 at 30 DAT (Fig. 3a) to 0.6833 at 60 DAT (Fig. 3b) and 0.8438 at 90 DAT (Fig. 3c). This indicates that plant height at later growth stages had a stronger association with grain yield compared to the early growth stage. A similar pattern has been reported in wheat, where models using single structural variables like LAI showed weak correlations at early growth stages ($R^2 \approx 0.13$ – 0.14) but markedly improved at mid-to-late stages ($R^2 \approx 0.66$ – 0.67), confirming that later-stage growth traits are more reliable predictors of yield (40). Plant height is recognised as a highly dynamic yield-affecting trait with strong associations with yield performance and studies on wheat genotypes under varying environments have demonstrated that the interrelationship between height and yield components becomes more pronounced as the crop approaches reproductive stages (41).

A similar positive trend was observed between total tillers per square metre and grain yield. The association was relatively weak at 30 DAT with an R^2 value of 0.2947 (Fig. 3d) but became stronger at 60 DAT ($R^2 = 0.8584$; Fig. 3e) and was highest at 90 DAT ($R^2 = 0.9724$; Fig. 3f). Among all the growth parameters studied under straw incorporation, total tillers per square metre at 90 DAT showed the strongest relationship with grain yield. This finding is consistent with investigations in European rice cultivars, where regression analysis confirmed that a greater number of tillers generally corresponds to increased yield and biomass accumulation, with positive regression slopes quantifying the contribution of each additional tiller to overall yield and suggesting that increasing tiller number is an effective strategy for enhancing rice productivity (42). Furthermore, research conducted under long-term paddy cultivation demonstrated that straw incorporation treatments consistently maintained a tillering advantage at maturity up to 13.64 % greater than the control which directly translated into a higher effective panicle number and consequently improved grain yield (43).

Leaf area index also exhibited a positive relationship with grain yield across all growth stages. The relationship improved progressively from 30 DAT ($R^2 = 0.3146$; Fig. 3g) to 60 DAT ($R^2 = 0.6007$; Fig. 3h) and further to 90 DAT ($R^2 = 0.9199$; Fig. 3i). This progressive improvement is supported by wheat growth monitoring studies demonstrating that LAI-based regression models achieve highest predictive accuracy during the flowering to grain-filling stages, confirming that canopy leaf area established during later crop growth stages is more closely associated with final grain yield than early-stage LAI measurements (44). The results clearly indicated that growth parameters recorded at later crop growth stages, particularly total tillers per square metre and LAI at 90 DAT, were more strongly associated with grain yield under varying levels of straw incorporation.

Regression analysis revealed a strong positive relationship between grain yield and growth parameters at different crop growth stages under varying N levels (Fig. 4). Plant height showed a progressively stronger association with grain yield from early to later growth stages. The R^2 increased from 0.8478 at 30 DAT (Fig. 4a) to 0.9564 at 60 DAT (Fig. 4b) and 0.9523 at 90 DAT (Fig. 4c), indicating that plant height measured during later growth stages was closely associated with grain yield. A positive relationship was also observed between total tillers per square metre and grain yield across all crop growth stages. The association was strongest at 30 DAT with an R^2 value of 0.9158 (Fig. 4d), followed by 90 DAT

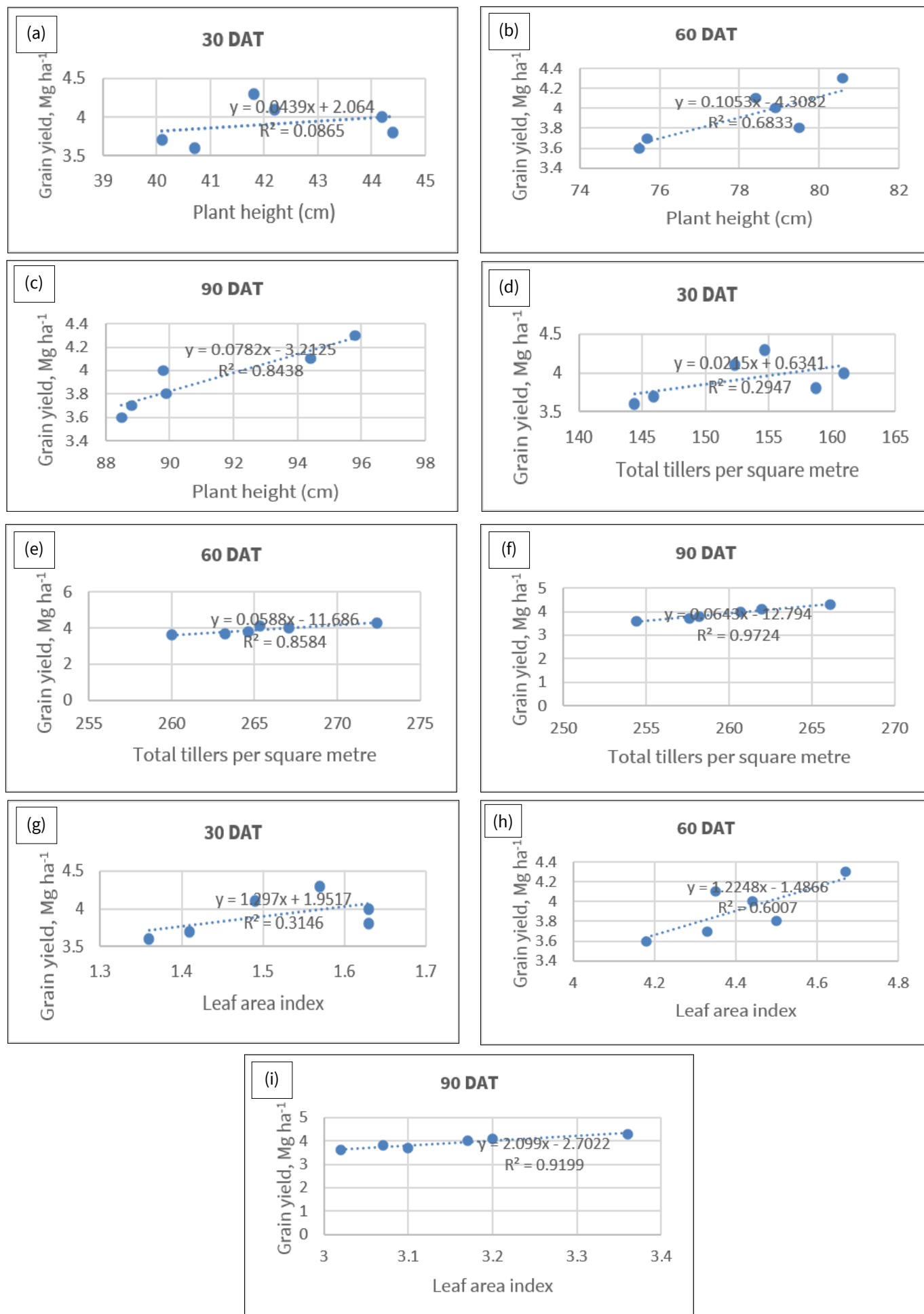


Fig. 3. Relationship of grain yield with plant height (cm), total tillers per square metre and leaf area index (LAI) at different crop stages under varying levels of straw incorporation.

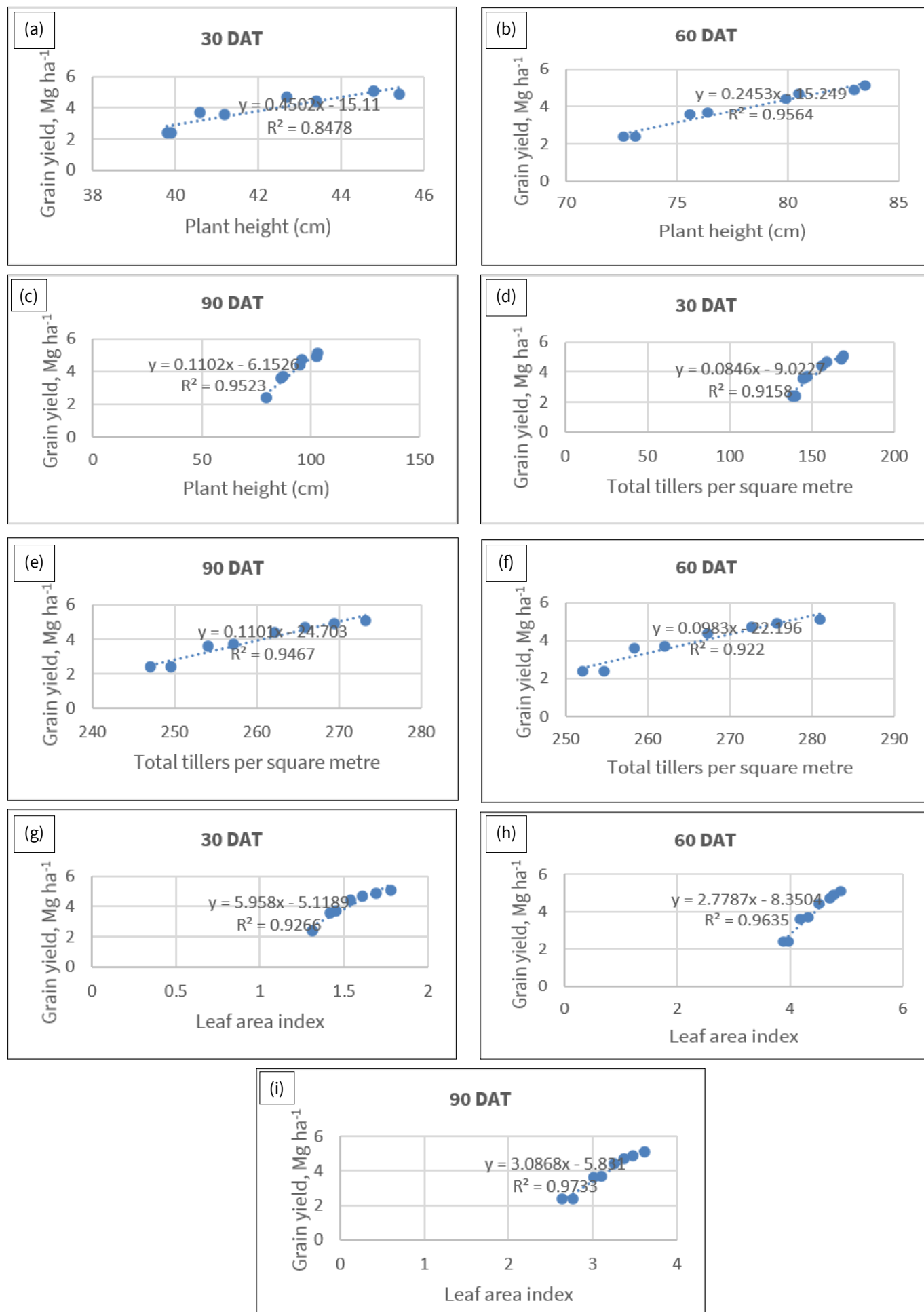


Fig. 4. Relationship of grain yield with plant height (cm), total tillers per square metre and leaf area index (LAI) at different crop stages under varying levels of nitrogen.

($R^2 = 0.9467$; Fig. 4e) and 60 DAT ($R^2 = 0.9220$; Fig. 4f). The consistently high R^2 values indicated a strong contribution of tiller production towards grain yield under varying N levels. This is corroborated by field studies on rice where N application at varying doses caused significant changes in plant height, total tiller number per m^2 and LAI and all three parameters showed strong association with grain yield, with panicle-bearing tiller being identified as the most influential parameter in multivariate analyses (45). Similarly, research in Jiangsu, China demonstrated that higher N supply increased both tiller number per unit area and LAI, with the combination of maximum tillers and spikelets per panicle being the primary determinant of optimum population productivity under varying N levels (46).

Similarly, LAI exhibited a strong positive relationship with grain yield at all growth stages. The R^2 increased from 0.9260 at 30 DAT (Fig. 4g) to 0.9635 at 60 DAT (Fig. 4h) and further to 0.9733 at 90 DAT (Fig. 4i). Among all the growth parameters studied under varying N levels, LAI at 90 DAT showed the strongest association with grain yield. This is in agreement with studies on rice where N level significantly influenced LAI values across the growing season, with higher N rates producing greater LAI at 60 DAT and beyond, indicating that N-driven canopy expansion during reproductive stages is a key driver of yield formation (47). Investigations across transplanted and direct-seeded rice systems further confirmed that higher N treatments (160 kg N ha^{-1}) consistently produced the highest number of effective tillers per hill and panicles per square metre and that the positive response of these yield-determining parameters to N was most pronounced during later crop growth stages (48). Overall, the regression analysis indicated that growth parameters recorded during later crop growth stages had a greater influence on grain yield under different N levels.

Conclusion

The present investigation demonstrated that rice straw incorporation and nitrogen (N) management significantly influenced the growth and rice productivity. Results clearly indicated that moderate straw incorporation (3 Mg ha^{-1}) significantly increased plant growth, total tiller production, leaf area index (LAI) and ultimately productivity of rice compared with higher straw incorporation (6 Mg ha^{-1}). Among the N levels, application of 120 kg N ha^{-1} consistently recorded superior growth and yield performance, indicating the importance of adequate N supply for sustaining higher productivity of rice. However, harvest index (HI) was maximised at 80 kg N ha^{-1} , suggesting relatively better partitioning efficiency at moderate N level. The combined effect of moderate rice straw incorporation and higher N application enhanced crop performance through greater degree of N availability. The findings of the study advocate the importance of incorporating rice straw at 3 Mg ha^{-1} along with application of 120 kg N ha^{-1} for achieving higher productivity and sustainable rice production. This strategy may help in effective utilisation of crop residues, the reduction of residue burning and the improvement of soil health while sustaining productivity of transplanted rainfed rice.

Acknowledgements

The authors are thankful to the Director of M S Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha, India, for providing the necessary academic environment, infrastructure and access to scientific resources for conducting this research work.

Authors' contributions

TS, SS and MDR contributed to the conceptualisation of the study. TS, SS and SM developed the methodology. SM carried out the investigation and data collection. SM and TS performed data curation and formal analysis. SM and SS conducted the literature review. SM prepared the original draft of the manuscript. TS, SS, BD, PB and MDR reviewed and edited the manuscript. TS and SS supervised the study, while BD, PB and MDR provided technical guidance and validated the findings. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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