International Journal of Plant & Soil Science

Volume 38, Issue 1, Page 272-283, 2026; Article no.IJPSS.151765
ISSN: 2320-7035

Assessment of Different Crop Establishment Methods and Nutrient Management Strategies Influencing Rice Growth under Rice-Wheat Cropping System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i15947

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/151765

Original Research Article

Received: 12/11/2025
Accepted: 19/01/2026
Published: 23/01/2026

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Cite as: *Jha, Sitesh, U P Singh, Anurag Upadhayay, Nikhil Kumar Singh, Somesh Jha, Shubham Sambhav Kamlapuri, Kajal Verma, and Deeptirekha Mahapatra. 2026. "Assessment of Different Crop Establishment Methods and Nutrient Management Strategies Influencing Rice Growth under Rice-Wheat Cropping System". International Journal of Plant & Soil Science 38 (1):272-83. https://doi.org/10.9734/ijpss/2026/v38i15947.*

Abstract

Rice-Wheat cropping system is a major food production system of the Indo-Gangetic Plains; however, its sustainability is increasingly challenged by intensive tillage, inefficient nutrient use, and declining soil health. A two-year field experiment was conducted at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, to evaluate the effects of crop establishment methods and nutrient management strategies on rice growth under the rice–wheat system. The experiment was laid out in a split-plot design with four crop establishment methods i.e. conventional puddled transplanted rice followed by conventional till wheat, conventional till direct-seeded rice followed by conventional till wheat, conventional till direct-seeded rice followed by zero-till wheat with rice residue retention, and zero-till direct-seeded rice followed by zero-till wheat with residue retention of rice and wheat and three nutrient management practices, namely farmer's practice, recommended fertilizer dose, and Rice–Wheat Crop Manager (RWCM)–based site-specific nutrient management. Results revealed that zero-till direct-seeded rice followed by zero-till wheat with residue retention significantly enhanced plant height, tiller density, dry matter accumulation, leaf area index, and chlorophyll content compared to conventional establishment practices at various growth stages. Among nutrient management strategies, RWCM-based site-specific nutrient management consistently improved rice growth parameters over farmer's practice and performed better than blanket fertilizer recommendations. The interaction between crop establishment and nutrient management was non-significant for most traits. Overall, the integration of conservation agriculture based crop establishment with RWCM-guided nutrient management proved effective in improving rice growth, resource-use efficiency, and system sustainability. Adoption of these practices may offer a viable strategy for enhancing productivity while conserving soil and water resources in the rice-wheat cropping system of the Indo-Gangetic Plains.

Keywords: Conservation agriculture; residue retention; resource-use efficiency; soil health; system sustainability.

1. Introduction

Grain crops, such as rice and wheat, are essential worldwide, and maximizing their production is a crucial task (Abd El-Reheem et al., 2022; Khater et al., 2023). Rice-Wheat (RW) cropping system is one of the most dominant and productive cereal-based systems in South Asia. It occupies nearly 13.5 million hectares in the Indo-Gangetic Plains (IGP), ensuring food and livelihood security for over 400 million people in the region (Upadhyay et al., 2024). In India, the RW system alone accounts for about 10.5 million hectares (Mha), while significant areas are also covered in Pakistan (2.2 Mha), Nepal (0.5 Mha) and Bangladesh (0.8 Mha). Despite its immense contribution to regional food security, the sustainability of the RW system, particularly rice production, is under growing stress (Kumar et al., 2019). High productivity achieved through conventional practices has relied heavily on intensive tillage, excessive irrigation, and imbalance nutrient use, leading to over-exploitation of natural resources such as soil, water, and energy. Rice plays a significant role in attaining food sufficiency and nutritional security in India (Harish et al., 2017). Direct Seeded Rice is advantageous over traditional planting as it avoids the cost of nurseries raising and transportation resulting delay of planting due to labour unavailability (Sarangi et al., 2014). This raises concerns regarding the long-term environmental, economic, and production sustainability of rice cultivation in the RW system. Although the green revolution contributed substantially to yield enhancement in the north-western IGP through improved varieties and better fertilizer use, the eastern IGP continues to lag (Harish et al., 2021; Das et al., 2023). The eastern region faces constraints such as small farm holdings, poor infrastructure, low adoption of advanced technologies, high population pressure, shorter wheat season after rice, and frequent climatic variability (floods, drought, extreme temperatures). These limitations collectively affect nutrient use efficiency and timely crop establishment of rice and wheat, posing a threat to productivity and farm profitability. RW system under conventional tillage faces multiple challenges including stagnant rice yields, rising production costs due to increasing labour and fuel use, declining soil organic carbon, falling groundwater levels, inefficient fertilizer utilization, and the emerging threat of climate change (Kumar et al., 2022). In order to improve productivity and grain quality, efficient nutrient use and soil fertility management practices should be adopted (Harish et al., 2018). Studies indicate that tillage and establishment operations alone constitute nearly 25-30% of production costs, reducing economic returns and often delaying sowing of succeeding crops, which leads to heat stress and lower productivity.

Conservation agriculture (CA) based crop establishment techniques offer potential solutions. Practices such as reduced soil disturbance, residue retention, and crop diversification improve soil quality, enhance water and nutrient use efficiency, and reduce production cost compared to conventional methods (Gathala et al., 2020). However, adoption remains limited, and nutrient management continues to be suboptimal due to blanket fertilizer recommendations and farmers' limited understanding of site-specific nutrient management (SSNM) principles. SNM was originally conceptualized in Asia for rice systems and emphasizes field-specific, dynamic nutrient application based on soil–plant interactions, optimizing nutrient supply in synchrony with crop demand. Recently, decision-support systems the Rice-Wheat Crop Manager (RWCM) a web based tool developed by IRRI provide scope to tailor fertilizer schedules under varying establishment methods to improve rice productivity and profitability (Upadhyay et al., 2024). Therefore, systematic assessment of interactions between crop establishment methods and fertilizer strategies is critical for enhancing rice yield, resource use efficiency, and long-term sustainability of the RW system in the Indo-Gangetic Plains.

2. Materials and Methods

The experiment was performed at the Agricultural Research Farm, IAS, BHU, which is roughly 2.5 km inland from the southern bank of the Ganga river in Varanasi. A two-year trial was conducted at 25°15' N latitude, 82°59' E longitude, and 75.7 m above mean sea level in the fertile alluvial soil of Northern Gangetic plains. The experimental field was homogenous in texture and topography with good fertility. Irrigation was done by tube wells and proper drainage facilities was ensured through the canals surrounding the experimental site.

The experimental soil was classified as Gangetic alluvial sandy clay loam with a pH of 7.34. It was moderately fertile, characterized by medium levels of available organic carbon (0.54%) and low level of nitrogen (211.52 kg ha^{-1}), while available phosphorus (24.46 kg ha^{-1}) and potassium (221.34 kg ha^{-1}) were in the medium range. The study was conducted using a split-plot design with three replications. Four crop establishment treatments were assigned to the main plots: conventional-till puddled transplanted rice followed by conventional-till wheat (CT PTR–CTW), conventional-till direct-seeded rice followed by CT wheat (CTDSR–CTW), conventional-till direct-seeded rice followed by zero-till wheat with rice residue retention (CTDSR–ZT wheat + RR), and zero-till direct-seeded rice followed by zero-till wheat with residue retention in both crops (ZTDSR–ZT wheat + RWR). Three nutrient management practices were allocated to sub-plots, namely farmer's practice (N1), recommended fertilizer dose (N2), and Rice–Wheat Crop Manager (RWCM)-based recommendations (N3), and were maintained during both years of experimentation.

The experimental area was tilled both wet and dry in the CTPTR method, then the field was levelled after puddling with a cage wheel. The CTDSR and ZTDSR treatments were seeded using a tractor-drawn zero-till seed-cum-fertilizer drill with a row spacing of 20.0 cm apart. The planter's depth control wheel was used to maintain the seeding depth at 2-3 cm. In ZTDSR seeds were sown without any prior tillage along with residue retention of wheat, and existing weeds in these plots were controlled by spot application of glyphosate (1.5%) before sowing. Under farmer's fertilizer practice, rice received 164 kg N, 50 kg P_2O_5, 32 kg K_2O, and 4 kg Zn ha^{-1}. Half of the nitrogen dose was applied basally at sowing along with the full doses of phosphorus and potassium, while the remaining nitrogen was top-dressed in two equal splits after the first and second irrigations. In the recommended fertilizer dose treatment, rice was supplied with 150 kg N, 60 kg P_2O_5, 60 kg K_2O, and 5 kg Zn ha^{-1} following the same nitrogen splitting schedule. In the RWCM treatment, fertilizer application was guided by crop manager recommendations, with nutrient rates of 101–32–34–5.25 kg N–P_2O_5–K_2O–Zn ha^{-1} during the first year and 102–33–35-5.25 kg N–P_2O_5–K_2O- Zn ha^{-1} during the second year.

3. Results

3.1 Plant Height (cm)

The observations on plant height of rice were recorded at 30, 60 and 90 DAS/DAT and at harvest, and the data are presented in Table 1. Crop establishment methods showed significant influence on rice plant height at all growth stages during both years of experimentation. Among the different establishment practices, ZTDSR–ZT wheat + RWR consistently produced taller plants compared to other treatments. Across the nutrient management options, RWCM-based nutrient management (N3) recorded greater plant height than farmer's practice, while the recommended fertilizer dose recorded intermediate values. The highest plant height was recorded with RWCM (N3) at 90 DAS/DAT, indicating the advantage of site-specific nutrient management in promoting vegetative growth of rice.

3.2 No. of Tiller Per m^2

Tiller count (m^{-2}) of rice were recorded at 30, 60 and 90 DAS/DAT and at harvest, and are presented in Table 2. Crop establishment methods significantly influenced tiller production at all growth stages during both years of the study. Among the establishment practices, ZTDSR–ZT wheat + RWR recorded significantly higher tiller counts compared to conventional tillage treatments at all observation stages. The maximum tiller count was observed under ZTDSR–ZT wheat + RWR at 60 DAS/DAT followed by CTDSR–ZT wheat + RR and CTDSR–CTW, whereas the lowest tiller numbers were consistently recorded under CT PTR–CTW during both years of experimentation. Nutrient management practices showed significant effect on tiller count of rice at all crop growth stages. Across sub-plot treatments, RWCM-based nutrient management (N3) produced significantly higher tiller counts compared to farmer's practice (N1), while the recommended fertilizer dose (N2) showed intermediate values. The highest tiller count was recorded with RWCM (N3) at 60 DAS/DAT, indicating the positive influence of site-specific nutrient application on tiller initiation and retention.

3.3 Dry Matter Accumulation (g m^{-2})

Dry matter accumulation of rice was significantly influenced by both crop establishment methods and nutrient management practices at all growth stages during both years of experimentation and depicted in table 3. Among the crop establishment treatments, ZTDSR–ZT wheat + RWR depicted higher dry matter accumulation throughout the crop growth period and recorded the maximum biomass at harvest, whereas the lowest values were observed under CT PTR–CTW.

Nutrient management practices also showed a significant effect, with RWCM-based site-specific nutrient management (N3) resulting in higher dry matter accumulation followed by N2 and N1.

3.4 Leaf Area Index (LAI)

Leaf area index (LAI) of rice was influenced by crop establishment methods at 30, 60 and 90 DAS/DAT during both years of experimentation presented in Table 4. Among the establishment practices, ZTDSR–ZT wheat + RWR consistently recorded higher LAI values at 30, 60 and 90 DAS/DAT compared to conventional tillage-based systems, while the lowest LAI was observed under CT PTR–CTW. Nutrient management practices showed a variable response across growth stages. Differences among nutrient treatments were non-significant at 30 and 60 DAS/DAT; however, at 90 DAS/DAT, RWCM-based nutrient management (N3) resulted in significantly higher LAI followed by recommended fertilizer dose (N2) and farmer's practice (N3).

3.5 SPAD Reading

The chlorophyll content of rice leaves, measured in terms of SPAD values, showed noticeable variation due to different crop establishment methods across all observation stages in both years of study (Table 5). Rice grown under ZTDSR–ZT wheat + RWR exhibited higher SPAD readings at 30, 60 and 90 DAS/DAT, indicating improved chlorophyll retention and leaf greenness. In contrast, the lowest SPAD values were generally associated with CT PTR–CTW. The response of chlorophyll content to nutrient management practices varied with crop growth stage. Differences among nutrient treatments were statistically significant only at 60 DAS/DAT, where the RWCM-based nutrient management (N3) resulted in comparatively higher SPAD values than farmer's practice, while the recommended fertilizer dose showed comparable performance.

3.6 Grain and Straw Yield

Grain and straw yields were significantly affected by crop establishment methods during both years of study (2022 and 2023).

Table 1. Effect of crop establishment and nutrient management on plant height (cm) at different stages of rice

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT			At harvest		
	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data
Crop establishment (CE)												
CE1: CTPTR – CT wheat	26.59	27.35	26.97	53.18	55.55	54.37	83.24	82.94	83.09	80.17	83.58	81.88
CE2: CTDSR – CT wheat	28.31	29.05	28.68	57.98	58.81	58.40	85.68	87.25	86.47	83.46	85.26	84.36
CE3: CTDSR – ZT wheat	28.63	29.40	29.02	59.08	59.96	59.52	86.47	88.58	87.53	85.04	87.17	86.11
CE4: ZT rice – ZT wheat	29.97	30.79	30.38	62.39	65.32	63.86	90.13	92.20	91.17	88.65	92.04	90.35
Sem ±	0.53	0.52	0.53	0.72	0.69	0.71	1.10	1.05	1.08	0.99	0.95	0.97
CD (P=0.05)	1.56	1.50	1.53	2.30	2.18	2.24	3.30	3.18	3.24	3.12	2.99	3.06
Nutrient management (N)												
N1: Farmers Practices	27.293	27.873	27.58	54.873	55.783	55.33	83.113	83.963	83.54	81.473	82.753	82.11
N2: Recommendation Fertilizer Dose	28.413	29.353	28.88	58.903	59.423	59.16	86.743	88.093	87.42	84.733	87.643	86.19
N3: RWCM Recommendation	29.433	30.223	29.83	60.723	61.533	61.13	89.283	91.173	90.23	86.783	90.653	88.72
Sem ±	0.41	0.38	0.40	0.62	0.58	0.60	0.99	0.94	0.97	0.88	0.83	0.86
CD (P=0.05)	1.21	1.13	1.17	1.95	1.8	1.88	2.86	2.74	2.80	2.66	2.52	2.59
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 2. Effect of crop establishment and nutrient management on tiller count (m^{-2}) of rice at various crop growth stages

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT			At harvest		
	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data
Crop establishment (CE)												
CE1: CTPTR – CT wheat	140.94	144.52	142.73	352.13	360.59	356.36	333.99	340.81	337.4	303.13	309.13	306.13
CE2: CTDSR – CT wheat	229.85	233.97	231.91	366.25	376.80	371.53	351.71	355.99	353.85	323.78	327.16	325.47
CE3: CTDSR – ZT wheat	233.94	239.01	236.48	372.06	379.33	375.7	355.01	360.14	357.58	327.11	330.48	328.8
CE4: ZT rice – ZT wheat	243.28	248.32	245.8	382.55	389.22	385.89	369.05	371.93	370.49	339.03	345.11	342.07
Sem ±	1.64	1.61	1.63	3.41	3.34	3.38	3.23	3.18	3.21	3.11	3.04	3.08
CD (P=0.05)	4.84	4.67	4.76	10.25	10.00	10.13	9.81	9.64	9.73	9.54	9.41	9.48
Nutrient management (N)												
N1: Farmers Practices	203.63	206.91	205.27	360.27	368.53	364.40	343.25	348.03	345.64	316.48	320.61	318.55
N2: Recommendation Fertilizer	212.66	217.78	215.22	365.14	376.49	370.82	352.18	356.96	354.57	322.95	327.19	325.07

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT			At harvest		
	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data
Dose												
N_3: RWCM Recommendation	219.71	224.67	222.19	379.34	384.45	381.90	361.90	366.68	364.29	330.35	336.11	333.23
Sem ±	1.47	1.44	1.46	3.10	3.03	3.07	2.93	2.89	2.91	2.82	2.76	2.79
CD (P=0.05)	4.44	4.29	4.37	9.42	9.19	9.31	9.02	8.86	8.94	8.77	8.65	8.71
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 3. Effect of crop establishment and nutrient management on dry matter accumulation (g m^{-2}) of rice at various crop growth stages

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT			At harvest		
	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data
Crop establishment (CE)												
CE_1: CTPTR – CT wheat	79.67	81.13	80.4	307.75	311.65	309.7	820.17	800.61	810.39	878.77	886.24	882.51
CE_2: CTDSR – CT wheat	116.17	119.08	117.63	321.52	325.82	323.67	841.46	838.73	840.1	917.53	924.17	920.85
CE_3: CTDSR – ZT wheat	118.64	121.87	120.26	327.65	331.98	329.82	849.13	856.73	852.93	934.34	943.29	938.82
CE_4: ZT rice – ZT wheat	126.56	129.48	128.02	335.62	340.54	338.08	820.17	879.51	849.84	958.74	971.14	964.94
Sem ±	1.60	1.57	1.59	3.34	3.28	3.31	3.17	3.12	3.15	3.05	2.98	3.02
CD (P=0.05)	4.70	4.54	4.62	10.01	9.76	9.89	9.57	9.41	9.49	9.31	9.18	9.25
Nutrient management (N)												
N_1: Farmers Practices	106.48	109.19	107.84	316.31	319.91	318.11	819.90	825.04	822.47	899.38	908.86	904.12
N_2: Recommendation Fertilizer Dose	110.54	112.75	111.65	323.72	328.35	326.04	841.19	848.20	844.70	926.06	933.27	929.67
N_3: RWCM Recommendation	112.95	115.93	114.44	328.57	333.44	331.01	848.86	857.64	853.25	940.81	950.70	945.76
Sem ±	1.46	1.43	1.45	3.04	2.99	3.02	2.88	2.84	2.86	2.78	2.71	2.75
CD (P=0.05)	4.33	4.17	4.25	9.01	8.79	8.90	8.62	8.47	8.55	8.38	8.27	8.33
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 4. Effect of crop establishment methods and nutrient management practices on leaf area index of rice at various crop growth stages

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT		
	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data
Crop establishment (CE)									
CE1: CTPTR – CT wheat	1.12	1.15	1.14	3.21	3.24	3.23	3.38	3.40	3.39
CE2: CTDSR – CT wheat	1.31	1.33	1.32	3.31	3.33	3.32	3.47	3.50	3.49
CE3: CTDSR – ZT wheat	1.33	1.37	1.35	3.35	3.38	3.37	3.54	3.57	3.56
CE4: ZT rice – ZT wheat	1.36	1.41	1.39	3.43	3.46	3.45	3.61	3.66	3.64
Sem ±	0.04	0.04	0.04	0.06	0.06	0.06	0.06	0.06	0.06
CD (P=0.05)	0.13	0.12	0.13	0.19	0.18	0.19	0.20	19	9.60
Nutrient management (N)									
N1: Farmers Practices	1.14	1.17	1.16	3.23	3.26	3.25	3.40	3.42	3.41
N2: Recommendation Fertilizer Dose	1.33	1.35	1.34	3.33	3.35	3.34	3.49	3.52	3.51
N3: RWCM Recommendation	1.35	1.39	1.37	3.37	3.40	3.39	3.56	3.59	3.58
Sem ±	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06
CD (P=0.05)	NS	NS	NS	NS	NS	NS	0.16	0.15	0.16
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 5. Effect of crop establishment and nutrient management on chlorophyll content in leaves (SPAD value) of rice at various crop growth stages, grain and straw yield of rice at harvest

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT			Grain Yield (kg/ha)			Straw Yield (kg/ha)		
	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data	2022	2023	Pooled Data
Crop establishment (CE)															
CE1: CTPTR – CT wheat	31.04	31.15	31.10	34.03	34.12	34.08	30.89	31.00	30.95	4332.00	4387.14	4359.57	6627.83	6719.06	6673.45
CE2: CTDSR – CT wheat	32.16	32.32	32.24	35.16	35.32	35.24	31.90	32.08	31.99	4504.44	4566.60	4535.52	6864.43	6951.65	6908.04
CE3: CTDSR – ZT wheat	32.48	32.60	32.54	35.48	35.60	35.54	32.20	32.23	32.22	4639.78	4707.96	4673.87	7075.97	7179.23	7127.60
CE4: ZT rice – ZT wheat	33.89	34.14	34.02	36.89	36.84	36.87	33.30	33.49	33.40	4874.38	4944.56	4909.47	7408.81	7523.11	7465.96
Sem ±	0.67	0.66	0.67	0.69	0.67	0.68	0.65	0.62	0.64	49.12	46.12	47.62	63.16	61.16	62.16
CD (P=0.05)	2.19	2.11	2.15	2.24	2.18	2.21	2.17	2.07	2.12	161.41	153.39	157.40	191.49	184.47	187.98

Treatments	30 DAS/DAT			60 DAS/DAT			90 DAS/DAT			Grain Yield (kg/ha)			Straw Yield (kg/ha)		
	2022	**2023**	**Pooled Data**	**2022**	**2023**	**Pooled Data**	**2022**	**2023**	**Pooled Data**	**2022**	**2023**	**Pooled Data**	**2022**	**2023**	**Pooled Data**
Nutrient management (N)															
N_1: Farmers Practices	31.21	31.35	31.28	35.20	35.26	35.23	31.74	32.08	31.91	4416.81	4475.95	4446.38	6691.37	6734.48	6712.93
N_2: Recommendation Fertilizer Dose	31.45	31.61	31.53	36.45	36.43	36.44	32.32	32.37	32.35	4563.17	4627.32	4595.25	6966.05	7105.39	7035.72
N_3: RWCM Recommendation	31.55	31.73	31.64	37.54	37.74	37.64	32.08	32.48	32.28	4781.70	4850.87	4816.29	7325.93	7438.20	7382.07
Sem ±	0.59	0.58	0.59	0.62	0.59	0.61	0.58	0.54	0.56	43.11	39.10	41.11	60.15	57.14	58.65
CD (P=0.05)	NS	NS	NS	1.89	1.78	1.84	NS	NS	NS	139.34	122.30	130.82	189.46	178.44	183.95
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Among the crop establishment treatments, ZTDSR–ZT wheat + RWR consistently recorded the highest grain yield (4874.38 and 4944.56 kg ha^{-1}) and straw yield (7408.81 and 7523.11 kg ha^{-1}) during 2022 and 2023, respectively, and was significantly superior to the remaining treatments. The lowest grain and straw yields were observed under CTPTR–CTW in both years. The RWCM recommendation resulted in the maximum grain yield (4781.70 and 4850.87 kg ha^{-1}) and straw yield (7325.93 and 7438.20 kg ha^{-1}) during 2022 and 2023, respectively, and was significantly superior to recommended fertilizer dose and farmers' practice.

4. Discussion

The results of the present study clearly demonstrate that long-term conservation agriculture (CA)–based crop establishment practices, particularly zero-till direct-seeded rice followed by zero-till wheat with residue retention (ZTDSR–ZT wheat + RWR), substantially improved rice growth parameters across growth stages. Enhanced plant height, tiller density, dry matter accumulation, leaf area index (LAI), and chlorophyll content collectively indicate a more vigorous and efficient crop growth environment under CA-based management compared to conventional puddled transplanted rice (Upadhyay et al., 2024). The superior growth performance under direct-seeded rice can be attributed to the absence of transplanting shock, which typically delays early growth and establishment in puddled transplanted rice. In contrast, direct seeding allows uninterrupted root development, leading to rapid crop establishment and early canopy expansion. Residue retention under zero tillage further improves soil structure, increases soil organic carbon, and enhances soil moisture retention and infiltration while reducing evaporation and runoff losses (Kumar et al., 2019). These improvements collectively promote better nutrient availability and uptake, thereby supporting sustained vegetative growth. Similar advantages of DSR over puddled transplanted rice have also been reported earlier by Nandan et al., (2018); and Kumar et al., (2020). Improved plant height under ZTDSR–ZT wheat + RWR reflects favorable soil physical conditions and enhanced rhizosphere environment under conservation practices. Reduced soil disturbance and residue cover help maintain optimal soil temperature and moisture, facilitating better root growth and nutrient absorption, which are essential for cell elongation and overall plant vigour (Oishy et al., 2025). These findings indicate that CA-based establishment practices contribute positively to vegetative growth, a key determinant of yield formation in rice.

Tiller production, a critical yield-determining trait, was also significantly enhanced under conservation-based establishment. Improved soil aeration, reduced compaction, and moderated soil temperature under residue-retained zero-till systems likely promoted early tiller initiation and reduced tiller mortality at later stages (Chaudhary et al., 2024). The higher tiller retention observed under ZTDSR–ZT wheat + RWR suggests improved assimilate availability and resource-use efficiency compared to conventional tillage systems. Dry matter accumulation followed trends similar to tiller production and plant height, indicating cumulative benefits of improved photosynthetic efficiency and nutrient uptake under conservation agriculture. Residue retention enhances microbial activity and nutrient cycling, leading to sustained biomass production throughout the crop growth period (Sarkar et al., 2020). These findings emphasize the role of CA practices in improving overall system productivity through better soil–plant interactions. Leaf area index and SPAD values further confirmed improved canopy development and nitrogen status under ZTDSR–ZT wheat + RWR. Higher LAI reflects enhanced leaf expansion and light interception, while increased SPAD readings indicate better chlorophyll content and nitrogen availability (Singh et al., 2024). Conservation practices reduce nitrogen losses and improve nitrogen retention in soil, thereby enhancing photosynthetic capacity and delaying leaf senescence.

Across nutrient management treatments, RWCM-based site-specific nutrient management (SSNM) consistently improved growth attributes compared to farmer's practice. The superior performance of RWCM can be attributed to synchronized nutrient supply with crop demand, particularly during critical growth stages such as tillering and vegetative expansion (Shahi et al., 2022). Stage-specific improvements in LAI and SPAD values highlight the effectiveness of SSNM in maintaining crop vigour and improving nutrient use efficiency.

The higher grain and straw yields obtained under ZTDSR–ZT wheat + RWR can be attributed to the favourable soil conditions created under zero tillage, including improved soil structure, enhanced soil moisture conservation, and reduced soil disturbance. These conditions facilitate better root development, improved nutrient uptake, and higher biomass accumulation, which collectively contribute to increased grain and straw yields. Higher grain and straw yields under the RWCM recommendation may be attributed to balanced and site-specific nutrient application, which ensures synchronization of nutrient supply with crop demand. Enhanced nutrient use efficiency under RWCM-based management promotes greater dry matter production and effective partitioning of assimilates towards grain formation, resulting in increased yields (Upadhyay et al., 2024).

5. Conclusion

The present study demonstrated that crop establishment methods and nutrient management practices significantly influence rice growth under the rice–wheat cropping system. Among the establishment methods, zero-till direct-seeded rice followed by zero-till wheat with residue retention (ZTDSR–ZT wheat + RWR) consistently enhanced plant height, tiller density, dry matter accumulation, leaf area index, and chlorophyll content compared to conventional puddled transplanted rice followed by conventional till wheat. The superior performance of this conservation-based practice can be attributed to the absence of transplanting shock, improved soil physical conditions, enhanced soil moisture conservation, and better nutrient availability. Nutrient management based on Rice–Wheat Crop Manager (RWCM) recommendations further improved rice growth attributes by ensuring balanced and stage-specific nutrient supply, particularly nitrogen, which enhanced vegetative growth, tiller retention, and photosynthetic efficiency. RWCM-based site-specific nutrient management outperformed farmer’s practice and showed clear advantages over blanket fertilizer recommendations. Overall, the integration of conservation agriculture–based crop establishment with RWCM-guided nutrient management proved to be an effective strategy for improving rice growth, resource-use efficiency, and system sustainability. Adoption of these practices can help enhance productivity while conserving soil and water resources, making them suitable options for sustaining the rice-wheat cropping system in the Indo-Gangetic Plains. Despite being a long term trial, this study was confined to a single location with limited treatment combinations, which may restrict wider exploration across diverse agro-climatic conditions. Furthermore, detailed assessments of soil biological dynamics and broader grain quality parameters needs to be explored. Hence, the future research should focus on multi-location validation of crop establishment and nutrient management strategies and emphasing on soil biological process and grain quality attributes to enhance long-term sustainability and on-farm validation to support wider adoption of these practices for rice-wheat cropping system.

Disclaimer (Artificial Intelligence)

The author(s) declare that no generative artificial intelligence tools, including large language models (e.g., ChatGPT, Copilot) or text-to-image generation technologies, were used in the preparation or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/151765