Indian Journal of Agronomy **70** (3): 249–258 (September 2025)
DOI: 10.59797/ija.v70.i3.5613

Research Paper

Improving rice productivity and soil nutrient availability through establishment and input management approaches

NIHAL CHANDRA MAHAJAN[1], RAJESH KUMAR SINGH[2], RAM KUMAR SINGH[3], UDAI PRATAP SINGH[4], ANURAG UPADHYAY[5] AND N. ANTHONY BAITE[6]

Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh 221 005

Received: December 2024; Revised accepted: May 2025

ABSTRACT

The pursuit of enhanced rice productivity in India necessitates a comprehensive understanding of the interplay between crop establishment methods, irrigation schedules, and nitrogen management practices. This study investigates the effects of these factors on the growth and yield of rice (*Oryza sativa* L.), employing a split-plot experiment design. The experiment examined two crop establishment methods of direct-seeded rice (DSR) and puddled transplanted rice (PTR), three irrigation schedules of I_1 (continuously submerged, CS, of 5 ± 2 cm depth), I_2 (intermittent submergence of 5 ± 2 cm with irrigation after five days of water disappearance from the soil surface), and I_3 (intermittent submergence of 5 ± 2 cm with irrigation after ten days of water disappearance from the soil surface) with four nitrogen management strategies of N_1 (recommended dose of nitrogen, RDN), N_2 (LCC threshold ≤ 4), N_3 (SPAD 30), and N_4 (Rice-Wheat Crop Manager recommendation, RWCM). The study found significant variations in rice growth parameters, yield components, and water efficiency due to the different treatments. Among the crop establishment methods, DSR demonstrated superior performance in terms of plant height, dry matter accumulation, crop growth rate (CGR), leaf area index (LAI), seed yield, and straw yield compared to PTR. In irrigation management, I_2 exhibited superiority in all growth and yield parameters as well as soil nutrient status and water use efficiency. Nitrogen management through RWCM was found to be the most efficient and significantly higher aforementioned parameters recorded compared to the other nitrogen management treatments. RWCM's tailored recommendations ensured optimal nitrogen availability, enhancing plant growth and yield outcomes.

Key words: Direct-seeded rice (DSR), Irrigation management, Nitrogen management, Rice productivity, Water use efficiency

Rice (*Oryza sativa* L.) is the most crucial cereal crop for many Asian countries, including India. Globally, rice ranks third in production, following sugarcane and maize, and is an essential commodity for basic nutrition, providing approximately 20% of the world's caloric intake. With global rice consumption exceeding 520 million metric tons, over 50% of the world's population depends on rice daily, according to the United Nations Food and Agriculture Organization. Rice is a water-intensive crop, requiring 3,000 to 5,000 liters of water/kilogram produced, making it particularly vulnerable to the increasing and severe droughts caused by climate change. Rising temperatures, floods, and unpredictable weather patterns are also leading to crop failures, which significantly impact the 150 million small-scale rice farmers dependent on rice cultivation for their livelihood. Projections indicate that climate change could reduce rice yields by 15% by 2050 (Singh *et al.,* 2017a).

In response to these challenges, researchers are exploring potential technologies and production systems to enhance rice cultivation sustainability. Direct-seeded rice has garnered significant interest due to its potential water, energy, labour, and cost efficiencies (Joshi *et al.,* 2018), compared to traditional transplanting methods. Additionally, techniques such as alternate wetting and drying (AWD) and intermittent irrigation are being investigated to reduce water use and greenhouse gas emissions. Nutrient management is also critical for successful crop production. Rice, like all crops, requires precise nutrient applications to optimize growth and yield (Samant *et al.,* 2023). Various precision nitrogen application technologies, such as the leaf colour chart (LCC), soil plant analysis development (SPAD) meter, and Rice-wheat crop manager recommendation (RWCMR), have been developed to meet these needs, each offering distinct advantages under specific conditions.

Based on a part of Ph.D. Thesis of the first author submitted to Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh in 2020 (unpublished)

---

[1]**Corresponding author's Email:** nihalchandra1996@gmail.com
[1,5,6]Ph.D. Scholar, [2]Professor, [3,4]Senior Professor, Department of Agronomy Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh 221 005

Crop establishment methods, irrigation water and nitrogen management are critical factors influencing rice production. These agronomic practices are interrelated and play a significant role in determining the growth, yield, and resource use efficiency of rice crops. Field experiments across various geographical locations have demonstrated that the choice of crop establishment method, the timing and mode of irrigation, and the strategy for nitrogen application can markedly affect rice yields and the sustainability of rice production systems (Chhabra *et al*., 2024). Interestingly, while some studies have shown that specific establishment methods such as the direct seeding can enhance grain yield and net returns (Xu *et al.,* 2019), others have highlighted the importance of irrigation and nitrogen management in optimizing rice production. For instance, alternate wetting and drying irrigation has been found to increase yield and water productivity (Su *et al.,* 2023), and the timing of nitrogen fertilizer application can influence the efficiency of nitrogen use and crop yields (Su *et al.,* 2023). Additionally, the integration of nitrogen management strategies with rainfall-adapted irrigation has been shown to synergistically improve grain yield and resource use efficiency (Yan *et al.,* 2022).

Given this background, an experiment was conducted to evaluate the effects of different crop establishment methods, irrigation schedules, and nitrogen management practices on the growth, yield, water use and soil nutrient status in rice.

MATERIALS AND METHODS

The experiment was conducted in the Agricultural Research Farm of Institute of Agricultural Sciences, Banaras Hindu University during the *Kharif* season of 2019 and 2020. The farm lies between the latitudes of 25°18' North and 82°59' East longitudes and an altitude of 75.7 meters above the mean sea level (AMSL) in the Northern Gangetic Alluvial Plains of Uttar Pradesh. The total rainfall during the experimental years was 1237.2 mm in 2019 and 1054.6 mm in 2020. The mean weekly maximum temperatures during the crop seasons ranged from 27.3°C to 36.4°C in both years, while the mean weekly minimum temperatures ranged from 11.2°C to 25.1°C. The weekly mean maximum relative humidity was 67–93% (average 85.13%) in 2019 and 72–95% (average 84.96%) in 2020. The weekly mean minimum relative humidity ranged from 40–82% (average 63.13%) in 2019 and 42–88% (average 65.75%) in 2020. Sunshine hours ranged from 0.1–9.6 hours in 2019 and 1.4–8.3 hours in 2020. The initial soil analysis indicated a sandy clay loam texture with a pH of 7.21. The soil contained 0.39% organic carbon, and the available nutrient levels were 229.12 kg/ha of nitrogen, 17.24 kg/ha of phosphorus, and 175.35 kg/ha of potassium.

The experiment, conducted in a split-plot design with three replications, featured two planting techniques and three irrigation schedules in the main plot and four precision nitrogen management techniques in the sub-plot (Table 1). The HUR 105 rice variety was sown in 72 plots. Each main plot measured 20 m × 3 m, while each sub-plot within it measured 4 m × 3 m, with a 1 m buffer zone between adjacent main plots. For direct-seeded rice (DSR), the field was prepared by ploughing twice with a disc harrow and once with a cultivator. Furrows were manually opened at a 20 cm row spacing, and seeds were sown at a rate of 30 kg/ha. Sowing of DSR and sowing in nursery for transplanting was done on 16.06.2019 in the first year and

Table 1. Detail of treatments

Treatment		Symbol
Main-plots treatment		
I. Crop Establishment		
(i)	Puddle Transplanted Rice (PTR)	CE_1
(ii)	Direct Seeded Rice (DSR)	CE_2
II. Irrigation scheduling		
(i)	Continuously submerged (CS) of 5 ± 2 cm depth	I_1
(ii)	Intermittent submergence (IS) of 5 ± 2 cm and irrigation after five days of disappearance of water from the soil surface	I_2
(iii)	Intermittent submergence of 5 ± 2 cm and irrigation after ten days of water disappearance from the soil surface	I_3
Sub-plots treatment		
I. Nitrogen Management		
(i)	RDN	N_1
(ii)	LCC threshold ≤ 4	N_2
(iii)	SPAD 30	N_3
(iv)	Rice – Wheat Crop Manager Recommendation	N_4

17.06.2020 in the following year. For puddled transplanted rice, the field was ploughed twice using an MB plough, followed by planking and levelling. Transplanting of rice seedlings into the main field was done on 07.07.2019 and 08.07.2020. The field was irrigated with 2–3 cm water level for puddling, and 21 days old seedlings were transplanted at 20 × 15 cm spacing with 2–3 seedlings per hill. The details of nutrient management as per treatment are provided in Table 2. The application of nutrients to the test crop was made based on recommendations and uniform application of phosphorous, potassium, and zinc (60-60-5 kg/ha) for all the treatments. The sources used for nitrogen, phosphorous, potassium, and zinc were urea (46% N), single super phosphate (16% P_2O_5, 12% S, and 21% Ca), muriate of potash (60% K_2O), and zinc sulphate monohydrate (33%), respectively. The total diammonium phosphate and potash dose were applied when sowing/transplanting as basal. Zinc was applied through 2 foliar sprays. Other agronomic practices were carried out as per the state recommendations. Nitrogen was applied as per treatments through leaf colour chart (LCC) threshold ≤ 4, SPAD 30, and Rice-Wheat crop manager recommendation, whereas in the recommended dose of nitrogen (120 kg/ha), one-fourth dose was applied as basal, the half dose was applied at the maximum tillering stage, and the remaining one-fourth dose at the panicle initiation stage. The recorded data were calculated using the following:

The crop growth rate was calculated per the formula Radford gave (1967) and expressed as $g/m^2/day$.

$$\text{Crop growth rate}(g/m^2/day) = \frac{w_2 - w_1}{t_2 - t_1}$$

Where,

W_1 = Total dry matter of crop plant at time interval t_1

W_2 = Total dry matter of crop plant at time interval t_2

Leaf area measured through Systronics leaf area meter-211 was divided by ground area to calculate leaf area index at 30, 60, and 90 DAS/DAT. The formula suggested by Radford (1967) was used as given here:

$$\text{Leaf area index (LAI)} = \frac{\text{Total leaf area }(cm^2)}{\text{Unit land area }(cm^2)}$$

Harvest index was computed using the following formula given by Nichiporovich, 1967.

$$\text{Harvest index (\%)} = \frac{\text{Economic yield (grains)}}{\text{Biological yield (grains + straw)}} \times 100$$

Water use efficiency (WUE) of different treatments was computed by dividing the economic yield (kg/ha) by the total amount of water used (cm) from the respective plots (Michael *et al.,* 1977).

$$\text{Water use efficiency (WUE)} = \frac{\text{Economic Yield (kg/ha)}}{\text{Total Consumptive Use of Water (cm)}}$$

RESULTS AND DISCUSSION

Growth parameters

Effect of crop establishment methods

Data from Table 4 and 5 indicate that crop establishment significantly influenced the various growth attributes of rice such as plant height, dry matter accumulation, leaf area index and crop growth rate. At 30 and 90 DAS, DSR recorded a plant height of 37.5 and 105.3 cm respective in the first year and 38.4 and 107.4 cm respectively, in the following year. This value recorded under DSR is 8.8% higher than puddled transplanted rice at 30 DAS in the first year and 8.7% higher in the following year. Similarly at 90 DAS, DSR recorded 5.0% and 4.9% higher plant height in the first and second year respectively. Throughout the

Table 2. Nutrient management scheduling as per treatment

Treatments details	Number of splits		Time of N application (DAS/DAT)		Total N applied (kg/ha)	
	2019	2020	2019	2020	2019	2020
RDN						
For TPR	3		0, 35, 63		30+60+30=120	
For DSR	3		0, 35, 63		30+60+30=120	
LCC threshold ≤ 4						
For TPR	5		25,45,65,85, 95		23+23+23+23+23=115	
For DSR	5		25,45,65,85, 95		23+23+23+23+23=115	
SPAD 30						
For TPR	5		25,45,65,85, 95		23+23+23+23+23=115	
For DSR	5		25,45,65,85, 95		23+23+23+23+23=115	
Rice-Wheat Crop Manager Recommendation						
For TPR	3		0, 40, 70		33+38+38=109	
For DSR	3		0, 48, 85		33+38+38=109	

Table 3. Total rainfall, effective rainfall and irrigation water applied as per treatment

Irrigation treatment	Consumptive use (mm)		Total rainfall (mm)		Effective rainfall (mm)		Irrigation water applied (mm)	
	2019	2020	2019	2020	2019	2020	2019	2020
Continuously submerged at 5 cm depth	1579.0	1556.03	1140.3	1363.66	722.88	681.83	856.12	874.20
Intermittent submergence of 5 ± 2 cm and irrigation after 5 days of disappearance of water from the soil surface	1524.5	1501.48	1140.3	1363.66	722.88	681.83	801.62	819.65
Intermittent submergence of 5 ± 2 cm and irrigation after 10 days of disappearance of water from the soil surface	1409.3	1386.33	1140.3	1363.66	722.88	681.83	686.42	704.50

All the data collected were subjected to Analysis of Variance (ANOVA) at $p \leq 0.05$ as described by Gomez and Gomez (1984) using statistical tool for agricultural research" (STAR v.2.0.1). For all graphical illustration, OriginPro, Version 2025 (OriginLab Corporation, Northampton, MA, USA) was used.

period of study, DSR was found more suitable, giving a superior growth attributes compared to TPR. The higher value of dry matter accumulation (31.8 and 174.4 g/m row length; 35.1 and 179.6 g/m row length), CGR (5.3 and 17.0 g/m^2/day; 5.8 and 17.2 g/m^2/day), LAI (1.3 and 3.7; 1.4 and 3.7) at 30 and 90 DAS respectively, in the first and second year was recoded under DSR. These findings could be attributed to the faster initial growth under DSR due to the direct sowing of seeds, leading to earlier establishment and a competitive advantage over weeds. This early establishment phase allows DSR plants to utilize available resources such as light, water, and nutrients more efficiently from the start, promoting faster vertical growth compared to transplanted rice which takes time to recover and establish after transplanting. Due to their early and rapid growth, plants can establish a robust canopy faster than PTR plants. This larger canopy can enhance photosynthetic efficiency and biomass accumulation (Bi and Zhou, 2021). DSR plants often establish a more extensive leaf area quickly, enhancing their photosynthetic capacity. This larger leaf area index (LAI) increases light interception and photosynthetic efficiency, contributing to a higher CGR (Dongre *et al.,* 2023).

Effect of irrigation scheduling

A significant influence of irrigation scheduling was observed during the study period on the crop's growth attributing factors (Table 4 and 5). At 30 DAS, intermittent submergence of 5 ± 2 cm and irrigation after 5 days of disappearance of water from the soil surface (I_2) recorded the highest plant height (39.0 and 39.9 cm), dry matter content (29.4 and 32.9 g/m row length), CGR (4.9 and 5.4 g/m^2/day) and LAI (1.2 and 1.3) in the first and second year respectively. Similarly, at 90 DAS, I_2 recorded the highest values in terms of plant height (106. and 109.2 cm), dry matter accumulation (178.6 and 183.3 g/m row length), CGR (17.4 and 17.7 g/m^2/day) and LAI (3.8 and 3.9). This finding suggests that the balance between water availability and periods of aeration in I_2 enhances cell elongation and overall plant vigour. In contrast, continuous submergence in I_1, while preventing water stress, may limit oxygen availability to roots, resulting in a significant reduction in soil redox potential and the heavy influx of flood water promotes runoff, volatilization and deep percolation which leads to loss of sizeable amount of nutrients and ultimately causes nutrient deficiency in soil (Kumar *et al.,* 2021), which may slightly inhibit height growth. The longer intervals between irrigations in I_3 likely induced periodic water stress, leading to reduced plant height compared to I_2. Throughout the period of study, the lowest plant height, dry matter, CGR and LAI was observed under treatment involving intermittent submergence of 5 ± 2 cm and irrigation after 10 days of disappearance of water from the soil surface (I_3)

Effect of nitrogen management practices

Nitrogen management through Rice-wheat crop manager (RWCM) was found significantly higher than other treatments in terms of CGR and LAI but reported to be at par with LCC threshold ≤ 4 under plant height and dry matter accumulation (Table 4 and 5). This trend was observed during both years of study and under both the days of observation. Nonetheless, RWCM recorded the highest plant height (38.0 and 108.4 cm; 39.1 and 110.4 cm), dry matter accumulation (30.4 and 180.4 g/m row length; 33.5 and 185.7 g/m row length), CGR (5.0 and 17.3 g/m^2/day;

Table 4. Effect of crop establishment, irrigation schedule, and precision nitrogen management on plant height and dry-matter accumulation of rice at 30 and 90 DAS

Treatment*	Plant height (cm)				Dry-matter accumulation (g/m row length)			
	30 DAS/DAT		90 DAS/DAT		30 DAS/DAT		90 DAS/DAT	
	2019	2020	2019	2020	2019	2020	2019	2020
Main-plots treatment								
Crop establishment								
CE_1	34.4	35.3	100.2	102.4	24.9	27.9	166.8	171.8
CE_2	37.5	38.4	105.3	107.4	31.8	35.1	174.4	179.6
SEm±	0.57	0.56	1.54	1.58	0.39	0.43	2.40	2.47
CD (P=0.05)	1.80	1.77	4.85	4.97	1.21	1.36	7.57	7.79
Irrigation scheduling								
I_1	35.5	36.3	103.2	105.8	28.5	31.7	170.6	175.9
I_2	39.0	39.9	106.4	109.2	29.4	32.9	178.6	183.3
I_3	33.4	34.5	98.6	99.7	27.1	29.9	162.6	167.9
SEm±	0.70	0.69	1.89	1.93	0.47	0.53	2.94	3.03
CD (P=0.05)	2.21	2.17	5.94	6.09	1.49	1.66	9.27	9.53
Sub-plots treatment								
Nitrogen Management								
N_1	34.5	35.1	96.6	97.9	26.1	29.5	160.9	166.0
N_2	35.0	35.9	101.0	103.7	27.8	31.0	166.8	171.9
N_3	36.5	37.3	104.9	107.5	28.9	31.9	174.4	179.4
N_4	38.0	39.1	108.4	110.4	30.4	33.5	180.4	185.7
SEm±	0.63	0.62	1.73	1.77	0.46	0.51	2.69	2.77
CD (P=0.05)	1.81	1.78	4.98	5.07	1.31	1.45	7.72	7.95

*For treatment details, please refer Table 1.

5.6 and 17.6 g/m^2/day) and LAI (1.3 and 3.8; 1.4 and 3.8) at 30 and 90 DAS and in the first and second year respectively. RWCM approach likely provided a more tailored nitrogen application, aligning with the specific needs of the crop at various growth stages. Such precision in nitrogen management ensures that plants receive adequate nutrients for optimal growth, promoting cell elongation and overall plant height, biomass accumulation, LAI and CGR. In contrast, the RDN approach might provide nitrogen in less optimal amounts or timing, and sensor-based methods (LCC and SPAD) could have had limitations in consistently detecting the precise nitrogen needs.

Yield parameter

Effect of crop establishment methods

The crop's seed yield, straw yield and harvest index were significantly influence by the crop establishment method (Table 6). In the first year, DSR recorded a seed yield of 4661 kg/ha, straw yield of 6974 kg/ha and harvest index of 40.0%. In the second year, the DSR recorded 10% higher seed yield, 7.4% higher straw yield and 2.9% higher harvest index compared to PTR. The enhanced vegetative growth and better overall plant health in DSR could have contributed to the increased yield attributes. Singh *et al*. (2017b) found that DSR promotes better biomass accumulation, leading to higher straw yields. Farooq *et al*. (2011) and Chauhan *et al*. (2017) also demonstrated that DSR can lead to higher grain yields due to improved plant establishment and reduced labour and water inputs. A higher harvest index in DSR suggests more efficient partitioning of biomass to the grain. Studies by Pathak *et al*. (2011) and Pandey and Velasco (2002) also reported that DSR can improve harvest index by promoting better resource allocation and reducing losses during establishment.

Effect of irrigation scheduling

The irrigation scheduling had a profound impact on the crop's seed yield, straw yield and harvest index (Table 6). In the initial year, intermittent submergence of 5 ± 2 cm and irrigation after 5 days of disappearance of water from the soil surface (I_2) achieved a seed yield of 4870 kg/ha, a straw yield of 7068 kg/ha, and a harvest index of 40.8% which was higher than the rest of the irrigation scheduling treatment. In the subsequent year, similar trend was

Table 5. Effect of crop establishment, irrigation schedule, and precision nitrogen management on CGR and LAI of rice at 30 and 90 DAS.

Treatment*	CGR ($g/m^2/day$)				LAI			
	30 DAS/DAT		90 DAS/DAT		30 DAS/DAT		90 DAS/DAT	
	2019	2020	2019	2020	2019	2020	2019	2020
Main-plots treatment								
Crop establishment								
CE_1	4.1	4.6	16.5	16.7	1.1	1.1	3.6	3.7
CE_2	5.3	5.8	17.0	17.2	1.3	1.4	3.7	3.7
SEm±	0.06	0.07	0.23	0.24	0.02	0.02	0.05	0.05
CD (P=0.05)	0.20	0.23	0.74	0.75	0.05	0.06	NS	NS
Irrigation scheduling								
I_1	4.7	5.2	16.8	17.0	1.2	1.3	3.7	3.7
I_2	4.9	5.4	17.4	17.7	1.2	1.3	3.8	3.9
I_3	4.5	4.9	16.1	16.2	1.1	1.2	3.5	3.5
SEm±	0.08	0.09	0.29	0.29	0.02	0.02	0.06	0.07
CD (P=0.05)	0.25	0.28	0.91	0.92	0.06	0.07	0.20	0.20
Sub-plots treatment								
Nitrogen Management								
N_1	4.3	4.9	16.3	16.5	1.1	1.2	3.5	3.6
N_2	4.6	5.1	16.5	16.7	1.2	1.2	3.6	3.6
N_3	4.8	5.3	17.0	17.2	1.2	1.3	3.7	3.7
N_4	5.0	5.6	17.3	17.6	1.3	1.4	3.8	3.8
SEm±	0.08	0.08	0.26	0.27	0.02	0.02	0.06	0.06
CD (P=0.05)	0.22	0.24	0.76	0.77	0.06	0.06	0.17	0.17

*For treatment details, please refer Table 1.

observed where I_2 continued to outperform the rest of the treatment. Throughout the study period, the lowest yield attributing factors were recorded with intermittent submergence of 5 ± 2 cm and irrigation after 10 days of disappearance of water from the soil surface (I_3). The positive impact of intermittent irrigation (I_2) on the growth attributes of rice has translated into improvements in yield parameters. These results align with the findings of Chapagain and Yamaji (2010) and dos Santos *et al*. (2024), which demonstrated that intermittent irrigation leads to higher yields.

Effect of nitrogen management practices

A significant influence of nitrogen management practices was observed on the seed yield, straw yield and harvest index of rice during the experimental period (Table 6). RWCM recorded the highest seed yield (4802 and 4987 kg/ha), straw yield (7098 and 7399 kg/ha) and harvest index (40.3 and 40.1%) in the first and second year respectively. This was followed by SPAD-30, LCC threshold ≤ 4 and RDN. The targeted application in RWCM may have ensured that nitrogen is not wasted, while also providing the crop with the necessary nutrients at the optimal time for uptake, leading to better growth and yield. This tailored approach enhances nitrogen use efficiency and minimizes losses due to leaching or volatilization, leading to improved plant growth and yield attributes (Balasubramanian, 2002; Witt *et al*., 2007). The use of RWCM, LCC threshold ≤ 4 and SPAD-30 for nitrogen management in crops like wheat and rice leads to higher yield attributes and seed yield due to the precise application of nitrogen when the plant needs it.

Soil nutrient status

Available nitrogen

Data from Fig. 1 indicate that direct-seeded rice (DSR) consistently outperformed puddled transplanted rice (PTR) in soil nitrogen availability over both years. DSR exhibited nitrogen levels of 244.30 kg/ha and 238.99 kg/ha in the first and second years, respectively, while PTR showed lower nitrogen levels of 223.57 kg/ha and 216.87 kg/ha in the same periods.

Water management practices significantly influenced soil nitrogen availability, with treatment I_3 yielding the highest nitrogen levels of 245.87 kg/ha and 239.87 kg/ha in the first and second years, followed by I_2 with 232.86 kg/ha and 226.86 kg/ha. The lowest nitrogen levels were observed under treatment I_1, recording 223.07 kg/ha and 217.06 kg/ha in the respective years. Regarding nitrogen

Table 6. Effect of crop establishment, irrigation schedule, and precision nitrogen management on grain yield, strawy yield and harvest index

Treatment*	Grain yield (kg/ha)		Straw yield (kg/ha)		Harvest index (%)	
	2019	2020	2019	2020	2019	2020
Main-plots treatment						
Crop establishment						
CE_1	4,254	4,383	6,463	6,749	39.6	39.0
CE_2	4,661	4,822	6,974	7,251	40.0	40.2
SEm±	46	47	67	70	0.40	0.39
CD (P=0.05)	144	149	212	221	NS	NS
Irrigation scheduling						
I_1	4,501	4,646	6,779	7,061	39.9	39.7
I_2	4,870	5,015	7,068	7,339	40.8	40.6
I_3	4,002	4,147	6,309	6,601	38.7	38.6
SEm±	56	58	83	86	0.49	0.48
CD (P=0.05)	177	182	260	271	1.53	1.52
Sub-plots treatment						
Nitrogen Management						
N_1	4,086	4,176	6,338	6,598	39.1	39.0
N_2	4,311	4,495	6,581	6,847	39.5	39.5
N_3	4,632	4,753	6,859	7,156	40.2	39.8
N_4	4,802	4,987	7,098	7,399	40.3	40.1
SEm±	50	52	76	79	0.45	0.45
CD (P=0.05)	143	148	217	226	NS	NS

*For treatment details, please refer Table 1.

management, while no significant differences were found, the Recommended dose of fertilization (N_1) consistently resulted in the highest soil nitrogen content of 237.04 kg/ha in the first year and 233.04 kg/ha in the second year. Conversely, SPAD-30 (N_3) recorded the lowest nitrogen content across both years. Higher soil nitrogen in DSR may be attributed to reduced denitrification and better nitrogen retention under aerobic conditions compared to flooded PTR (Weller *et al.,* 2014). Consistently higher nitrogen levels under treatment I_3 suggest that optimal water availability supports microbial activity and minimizes nitrogen losses (Shekhar *et al.,* 2021). Although nitrogen management effects were not statistically significant, the trend under N_1 indicates that a stable, recommended fertilization dose helps maintain soil nitrogen levels effectively.

Available phosphorus

DSR consistently outperformed PTR in soil phosphorus availability over both years (Fig. 1). DSR showed phosphorus levels of 18.42 kg/ha and 16.44 kg/ha in the first and second years, respectively, while PTR exhibited lower phosphorus levels of 16.18 kg/ha and 14.56 kg/ha during the same periods. The absence of puddling in DSR reduces the destruction of soil aggregates and preserves beneficial microbial communities involved in phosphorus solubilization, thus contributing to higher phosphorus levels observed over both years. Similar finding was also reported by Hazra *et al.* (2024) where, DSR resulted in higher soil available P over PTR. Irrigation scheduling significantly influenced soil phosphorus availability, with treatment I_3 producing the highest phosphorus levels of 18.53 kg/ha and 16.72 kg/ha in the first and second years, respectively. Treatment I_2 followed closely with phosphorus contents of 17.38 kg/ha and 15.58 kg/ha. The lowest phosphorus levels were observed under treatment I_1, with 16.00 kg/ha and 14.21 kg/ha in the respective years. Under nitrogen management, the Rice-Wheat Crop Manager Recommendation (N_3) consistently resulted in the highest soil phosphorus content of 17.66 kg/ha in the first year and 15.84 kg/ha in the second year. Conversely, the lowest phosphorus content (16.92 kg/ha and 15.18 kg/ha) was recorded under RDN (N_1).

Available potassium

The study found that direct-seeded rice had significantly higher soil potassium content compared to puddled transplanted rice (Fig. 1). Direct-seeded rice recorded potassium levels of 197.71 kg/ha and 188.07 kg/ha in the first and

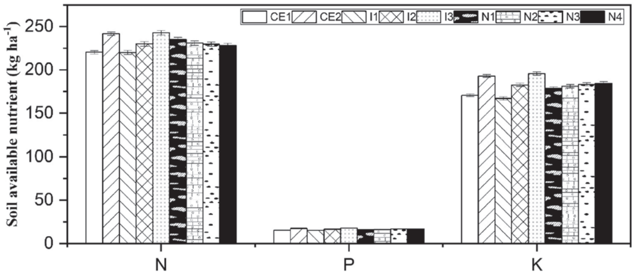

Fig. 1. Effect of crop establishment, irrigation schedule, and precision nitrogen management on soil available NPK (average data of 2 years)

second years, respectively, whereas puddled transplanted rice had potassium levels of 75.07 kg/ha and 166.37 kg/ha during the same periods. Higher soil potassium under DSR may be due to reduced leaching and better soil structure compared to flooded PTR conditions, which often enhance potassium loss (Mondal *et al.,* 2019). Additionally, irrigation scheduling had a notable impact on soil potassium content. Treatment I_3 showed the highest potassium content, with 200.23 kg/ha and 191.07 kg/ha in the first and second years, respectively, significantly higher than other water management treatments. Conversely, treatment I_1 recorded the lowest potassium content, with 171.64 kg/ha and 162.46 kg/ha in the respective years. Nitrogen management did not show significant effects on soil potassium content across both study years.

Water use

Irrigation water applied from sowing/transplanting to harvest (cm)

Fig. 2 presents data on irrigation water applied (cm) from sowing/transplanting to harvest, influenced by crop establishment method, irrigation scheduling, and nitrogen management. PTR required more irrigation water (36.89 and 45.76 cm) compared to DSR (31.67 and 40.89 cm) in the first and second years, respectively. DSR reduced water use by 16.48% and 11.91% in the two years. The least water application was recorded under intermittent submergence (I_3) at 30.98 and 37.76 cm, followed by I_2 (34.61 and 42.19 cm). Continuous submergence (I_1) required the highest water (38.97 and 47.87 cm). Differences between I_2 and I_3 were statistically insignificant. Nitrogen levels had no significant effect on irrigation water applied in either year.

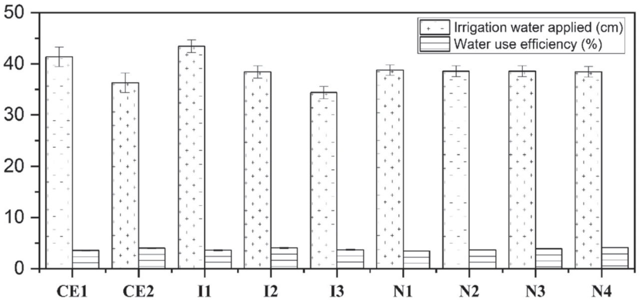

Fig. 2. Effect of crop establishment, irrigation schedule, and precision nitrogen management on irrigation water applied and water use efficiency (average data of 2 years)

Water use efficiency

The data in Fig. 2 show that crop establishment, water management, and nitrogen management practices had significant impacts on water use efficiency (WUE) over both experimental years. Direct-seeded rice demonstrated higher WUE, with values of 3.92% and 4.07% in the first and second years, respectively, compared to 3.49% and 3.61% for puddled transplanted rice. The higher WUE in DSR is attributed to more effective utilization of rainfall and reduced non-beneficial water losses (e.g., deep percolation and surface evaporation). Farooq *et al*. (2011) indicated that DSR systems have up to 40% higher WUE than puddled transplanting, primarily due to better water management and reduced wastage. Regarding irrigation scheduling, I_2 achieved the highest WUE of 3.98% and 4.09% in the first and second years, respectively, which were significantly higher than those under I_3 (3.61% and 3.76%). I_2 strikes a balance between water availability and water use, providing sufficient water during critical growth periods while avoiding excessive water application. This balance ensures that the water applied is used productively, leading to higher water productivity and increase water use efficiency. Comparing to I_3, which is an extended period of dry days, which may have led to some stress in plant, leading to lower utilization of water and some extent of moisture deprivation when needed. Gathala *et al*. (2011) demonstrated that optimal intermittent submergence regimes like I_2 can enhance water productivity and WUE. The lowest WUE was observed under I_1, with values of 3.52% and 3.66%. However, I_1 and I_3 did not show statistically significant differences. Nitrogen management also significantly influenced WUE. The Rice-Wheat Crop Manager Recommendation (N_4) resulted in the highest WUE (4.02% and 4.17%) compared to all other nitrogen management treatments. This was followed by SPAD 30 (3.85% and 3.96%), LCC threshold ≤ 4 (3.57% and 3.74%), and RDN (3.37% and 3.50%). Proper nitrogen management can enhance water use efficiency (WUE) and water productivity in rice cultivation by optimizing plant growth and development, leading to more effective utilization of water resources. According to Sinclair and Vadez (2012), optimized nitrogen application enhances root proliferation and depth, leading to better water extraction and utilization, thereby improving WUE.

Based on the two years of experimentation, direct seeded rice with Intermittent submergence of 5 ± 2 cm and irrigation after 5 days of disappearance of water from the soil surface along with Rice-Wheat crop manager can be recommended for better crop growth, yield, quality and economics of rice under Agro-climatic condition of Varanasi region.

REFERENCES

Balasubramanian, R. 2002. Response of hybrid rice (*Oryza sativa*) to levels and time of application of nitrogen. *Indian Journal of Agronomy* **47**(2): 203–206.

Bi, Y. and Zhou, H. 2021. Changes in peanut canopy structure and photosynthetic characteristics induced by an arbuscular mycorrhizal fungus in a nutrient-poor environment. *Scientific Report* **11**: 14832. https://doi.org/10.1038/s41598-021-94092-w

Chapagain, T. and Yamaji, E. 2010. The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. *Paddy and water environment* **8**: 81–90.

Chauhan, B.S, Mahajan, G., Sardana, V., Timsina, J. and Jat, M.L. 2017. Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: Problems, opportunities, and strategies. *Advances in Agronomy,* **117**: 315–369.

Chhabra, V., Sreethu, S. and Kaur, G. 2024. Wheat Growth and Yield in the Rice-Wheat Cropping System: Impact of Crop Establishment Techniques, Sowing Schedule and Nitrogen management. (Pre-print).

Dongre, A., Kumar, N., Rajput, J.S. and Mandal, S. 2023. Effect of integrated nutrient management on growth indices and yield of direct seeded rice (*Oryza sativa* L.) under midland situations of Bastar Plateau. *The Pharma innovation Journal* **12**(10): 2,048–2,052

dos Santos, M. P., Heinemann, A.B., Stone, L.F., da Silva, M.A.S., Lanna, A.C. and dos Santos, A.B. 2024. Phenology, gas exchange, biomass accumulation, and irrigated rice yield under alternative irrigation managements. *Agronomy Journal* **116**(2): 542–562.

Farooq, M., Siddique, K.H.M., Rehman, H., Aziz, T., Lee, D.J. and Wahid, A. 2011. Rice direct seeding: Experiences, challenges and opportunities. *Soil and Tillage Research* **111**(2): 87–98.

Gathala, M.K., Kumar, V., Sharma, P.C., Saharawat, Y.S., Jat, H.S., Singh, M. and Ladha, J.K. 2011. Optimizing intensive cereal-based cropping systems addressing current and future challenges. *Advances in Agronomy* **117**: 1–67.

Gomez, K.A., and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd ed., 680. New York: John Wiley and Sons.

Hazra, K.K., Swain, D.K., Singh, S.S. and Nath, C.P. 2024. System-based phosphorus management in non-flooded rice-lentil rotation in tropical alkaline soil on Gangetic plain: Crop productivity, phosphorus use efficiency and budgeting. *Field Crops Research* **315**: 109,438.

Joshi, J., Meena, S.L., Rathore, A.L., Tandon, A. and Sonit, A., 2018. Effect of crop establishment and irrigation methods on summer rice (*Oryza sativa*). *Indian Journal of Agronomy* **63**(2): 168–173.

Kumar, A., Nayak, A.K., Hanjagi, P.S., Kumari, K., Vijayakumar, S., Mohanty, S., Tripathi, R. and Panneerselvam, P. 2021. Submergence stress in rice: Adaptive mechanisms, coping strategies and future research needs. *Environmental and Experimental Botany* **186**: 104,448.

Michael, A.M., Hukkeri, S.B. and Singh, N.P. 1977. Estimating water requirement and irrigation management of crops in India. *ICAR Monograph No*., **4**: 91–91.

Mondal, S., Kumar, R., Karnena, K. R., Mishra, J. S., Poonia, S. P., Bhatt, B. P., Saurabh, K. and Chakraborty, D. 2019. Shortterm (5 years) impact of conservation agriculture on soil physical properties and organic carbon in a rice–wheat rotation in the IndoGangetic plains of Bihar. *European Journal of Soil Science* **71**(6): 1,076–1,089. https://doi.org/10.1111/ejss.12879

Nichiporovich, A.A. 1967. Aims of research on photosynthesis of plants as a factor of productivity. In: *Photosynthesis of Productive systems*. pp 3–36.

Pandey, S. and Velasco, L. 2002. Economics of direct seeding in Asia: Patterns of adoption and research priorities. *Direct Seeding: Research Strategies and Opportunities* 3-14.

Pathak, H., Tewari, A. N., Sankhyan, S., Dubey, D. S., Mina, U., Singh, V. K. and Jain, N. 2011. Direct-seeded rice: Potential, performance, and problems—A review. *Current Advances in Agricultural Sciences* **3**: 77–88.

Radford P.J. 1967. Growth analysis formula end their use abuse. *Crop science* **7**: 171–175.

Samant, T.K., Garnayak, L.M., Paikaray, R.K. and Mishra, P.J. 2023. Effect of rice-establishment methods and nutrient management on productivity, profitability and soil health under rice (*Oryza sativa*)-groundnut (*Arachis hypogaea*) cropping system. *Indian Journal of Agronomy* **68**(3): 253–259.

Shekhar, S., Mailapalli, D.R. and Raghuwanshi, N.S. 2021. Simulating nitrogen transport in paddy crop irrigated with alternate wetting and drying practice. *Paddy and Water Environment* **19**(3): 499–513. https://doi.org/10.1007/s10333-021-00850-x

Sinclair, T. R. and Vadez, V. 2012. The future of grain legumes in cropping systems. *Crop Science* **52**(3): 789–798.

Singh, K., McClean, C.J., Büker, P., Hartley, S.E. and Hill, J.K. 2017a. Mapping regional risks from climate change for rainfed rice cultivation in India. *Agricultural Systems* **156**: 76–84.

Singh, S., Bhushan, L., Ladha, J.K., Gupta, R.K., Rao, A. N. and Mortimer, M. 2017b. Weed management in direct-seeded rice: A review. *Crop Protection* **26**: 399–407.

Su, Q., Cang, B., Ullah, R., Song, Z., Li, Y., Cui, J., Wei, X., Yang, M., Yang, X. and Wu, Z., 2023. Interaction of the coupled effects of irrigation mode and nitrogen fertilizer timing on rice yield in different regions. *Irrigation and Drainage* **72**(4): 999–1,012.

Weller, S., Kraus, D., Ayag, K. R. P., Wassmann, R., Butterbach-Bahl, K., Alberto, M. C. R. and Kiese, R. 2014. Methane and nitrous oxide emissions from rice and maize production in diversified rice cropping systems. *Nutrient Cycling in Agroecosystems* **101**(1): 37–53. https://doi.org/10.1007/s10705-014-9658-1

Witt, C., Buresh, R.J., Peng, S., Balasubramanian, V. and Dobermann, A. 2007. Nutrient management. (In**)** Rice: A Practical Guide to Nutrient Management (2nd edition). International Rice Research Institute (IRRI), International Plant

Nutrition Institute (IPNI), and International Potash Institute (IPI).

Xu, L., Li, X., Wang, X., Xiong, D. and Wang, F. 2019. Comparing the grain yields of direct-seeded and transplanted rice: A meta-analysis. *Agronomy* **9**(11): 767.

Yan, J., Wu, Q., Qi, D. and Zhu, J. 2022. Rice yield, water productivity, and nitrogen use efficiency responses to nitrogen management strategies under supplementary irrigation for rainfed rice cultivation. *Agricultural Water Management* **263**: 107,486.