



Impact of drip fertigation on growth and yield of wheat in a conservation agriculture-based rice (*Oryza sativa*)-wheat (*Triticum aestivum*) system in eastern Indo-Gangetic plains of India

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ABSTRACT

A field experiment was conducted during 2022–23 and 2023–24 at the International Rice Research Institute-South Asia Regional Centre, Varanasi, Uttar Pradesh to assess the performance of wheat (*Triticum aestivum* L.) crop in 5-year long-term conservation agriculture (CA) based rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) system (RW) rotation using surface and sub-surface drip fertigation. The experiment was conducted in a randomized complete block design (RCBD) with nine treatment combinations and three replications. Results revealed that plant height, dry matter accumulation and leaf area index (LAI) of wheat at 30 days after sowing (DAS) showed non-significant differences across the imposed treatments. At 90 DAS, the highest plant height was observed in sub-surface drip fertigation (SSDF) and surface drip fertigation (SDF). Likewise, dry matter accumulation and LAI were higher at 90 DAS, in zero-till wheat (ZTW) under SSDF and SDF compared to ZTW with flood irrigation. Further, the study reveals that with 100% recommended dose of nitrogen (RDN) the grain yield of wheat was improved by 6% in ZTW plots followed by direct-seeded rice (DSR) plots compared to ZTW following PTR under flood irrigation plots. In addition, the SSDF and SDF resulted in yield increases of 24% and 20%, respectively as compared to CTW followed by PTR plots. Among the imposed treatments, ZTW-DSR-SSD-100N recorded the highest gross return (₹131,015) and net return (₹98,618), with the highest net BC ratio of 3.13, which is 8.5%, higher than the CTW-PTR-F-100N plots. These findings highlight the effectiveness of integrating DSR with drip fertigation technology in enhancing wheat productivity and economics under the CA-based RW system in the eastern Indo-Gangetic Plains.

Keywords: Direct seeded rice, Nitrogen doses, Sustainability, Zero-tilled wheat

Sustainability in agriculture is a growing concern, especially for the rice-wheat (RW) cropping system, which is crucial for food security in South Asia. In India, this system provides around 60% of the country's calorie intake and 40% of the food basket. With a rising population, rice and wheat production must increase by 1.1% and 1.7% annually to meet future demands, particularly in the Indo-Gangetic plains (Jat *et al.* 2020). However, the RW system, which is managed with traditional practices, faces sustainability challenges. Practices such as intensive tillage and puddling have led to declining groundwater levels, stagnant productivity, deteriorating soil health, and reduced economic returns (Sidhu *et al.* 2019). In a conventional RW system, rice is

grown under water-intensive puddling, and wheat is sown in dry soil after multiple tillage operations. This process delays wheat sowing by 10–15 days, causing the grain-filling period to coincide with hot winds, reducing yields. Additionally, repeated tillage and alternating water regimes between rice and wheat lead to subsoil compaction, which limits root growth and water movement (Sidhu *et al.* 2019).

Given these challenges, there is an insistent need for sustainable alternatives. With climate change projected to increase global water demand for irrigation by 40% by 2025, efficient water management is critical. Direct-seeded rice (DSR) offers a promising solution by reducing water use and creating better soil conditions for succeeding wheat crop under the RW system. Additionally, adopting zero tillage and integrating drip irrigation systems as surface and subsurface drip fertigation can improve water use efficiency, and nutrient availability, with lower production costs (Patra *et al.* 2023a). Furthermore, CA practices, including residue recycling, minimal soil disturbance, and

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efficient crop diversification, enhance water use efficiency, reduce energy use, and improve soil health and crop yields (Parihar *et al.* 2017, Patra *et al.* 2023b). However, studies on the combined effects of CA, drip fertigation and DSR in RW systems, especially in smallholder dominated eastern Indo-Gangetic plains, remain limited. Hence the present study aims to assess the growth and productivity of wheat under different crop establishment techniques, irrigation methods and nitrogen (N) levels in a long-term CA-based RW rotation.

MATERIALS AND METHODS

Site characteristics: A field experiment was conducted during 2022–23 and 2023–24 at the International Rice Research Institute-South Asia Regional Centre, Varanasi (25.31° N, 82.97° E), Uttar Pradesh. The experimental site falls under eastern Indo-Gangetic Plains of India in a humid subtropical climate with mean monthly temperatures ranging from 13.4°C in January and 32.7°C in June. The average annual rainfall was 1100 mm, with approximately 9.7 h of sunshine per day. The soil at the site is silty loam in texture with a pH of 7.8 and organic carbon content ranging from 0.52%–0.64%, with available nitrogen (182 kg/ha), phosphorus (22 kg/ha) and potassium (161 kg/ha).

Installation of drip fertigation system: In the surface drip fertigation (SDF) and sub-surface drip fertigation (SSDF), laterals with an inner diameter of 16 mm were installed at a 60 cm spacing to supply water and nutrients to three rows of wheat. In the SSDF, laterals were buried at a 10 cm depth, parallel to the crop rows. The in-line emitters spaced 30 cm apart, discharge water at a rate of 2.0 L/h. Nitrogen was fertigated using a venturi meter with the desired injection rate.

Detail of imposed treatments: An experiment was conducted during the *rabi* seasons of 2022–23 and 2023–24, to evaluate the combined effect of CA, drip fertigation and N levels on succeeding wheat crop in the RW system. Wheat was sown in the first fortnight of November using a ZT seed drill, with 30% of rice residues left over in the field in CA based treatment and no residue in CT plots. The wheat variety HD-2967 (145–155 days maturity period) was used for the experiment. The seeds were sown at a rate of 100 kg/ha, maintaining a row-to-row spacing of 20 cm. The experiment was conducted in a randomized complete block design (RCBD), comprising nine treatment combinations with three replications. Each experimental plot measured 35.0 m² (7.0 m × 5.0 m) in CA based treatments and no residue in CT plots. The imposed 9-treatments include, T₁, Zero-tilled wheat (ZTW) *fb* direct seeded rice (DSR) with flood irrigation and 75% recommended dose of nitrogen (RDN) (ZTW-DSR-F-75N); T₂, ZTW *fb* DSR with flood irrigation and 100% RDN (ZTW-DSR-F-100N); T₃, ZTW *fb* DSR with SDF and 75% RDN (ZTW-DSR-SDF-75N); T₄, ZTW *fb* DSR with SDF and 100% RDN (ZTW-DSR-SDF-100N); T₅, ZTW *fb* DSR with SSDF and 75% RDN (ZTW-DSR-SSDF-75N); T₆, ZTW *fb* DSR with SSDF and 100% RDN (ZTW-DSR-SSDF-100N); T₇, ZTW *fb* PTR with

flood irrigation and 75% RDN (ZTW-PTR-75N); T₈, ZTW *fb* PTR with flood irrigation and 100% RDN (ZTW-PTR-100N) and T₉, Conventional tilled wheat (CTW) *fb* PTR with 100% RDN as a farmers practice (CTW-PTR-100N). The recommended dose of fertiliser was 120:60:40 N, P₂O₅, K₂O. The full dose of P₂O₅ and K₂O and 30% nitrogen was applied as basal uniformly across all N management treatments. The remaining nitrogen was supplemented in three equal splits at critical stages of wheat. Irrigation was given at 50% depletion of available water, sensing through a pre-installed PR2 soil moisture profile probe (Delta-T Devices, UK).

Measurement of growth, phenology and yield attributes of wheat: After crop establishment, a 1 m row was marked in the 3rd row on both sides of each plot tangentially for recording biometric observations. Plant height was measured from five plants at the extremes of the marked row at periodic intervals. Similarly, from the 2nd row (both sides of the plot), plants in the 50 cm + 50 cm row lengths diagonally were clipped from the ground surface using a sickle for dry matter accumulation. The samples were air dried for 2–3 days and then placed in an oven for complete drying by maintaining a temperature of 65°C. Once the sample weight became constant it was recorded and expressed in terms of g/m². The leaf area index (LAI) was measured using the ACCUPAR LP-80 at 15-day intervals. Days to 50% anthesis and physiological maturity were recorded from the sowing date. At physiological maturity, the number of spikes in the marked row length was counted and expressed as spikes/m². The spike weight was determined by averaging the weight of five randomly selected spikes from each plot. Similarly, the number of grains/spike and grain weight/spike were also measured from these selected spikes. After drying and cleaning, a representative grain sample from each plot was used to measure the 1000-grain weight. The crop was manually harvested, leaving three border rows unharvested on both sides and 0.5 m along the length, resulting in a net plot size of 10 m². The total harvested produce, including both grain and straw, was weighed after sun/air drying and expressed as biological yield in tonnes per hectare (t/ha). After manual threshing, wheat grains were collected, oven-dried at 65–70°C for 48 h, and then weighed to determine grain yield, adjusted to a moisture content of 14% and expressed in t/ha. The harvested straw was sun-dried, weighed and similarly expressed in t/ha. The harvest index was calculated by dividing the economic yield (grain yield) by the biological yield (total produce) and expressed as percentage:

$$\text{Harvest index (HI)} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

Statistical analysis: The analysis of variance (ANOVA) was built using the agricolae package in R software. Differences between treatment means were assessed through the LSD test at a significance level of P<0.05, as described by Gomez and Gomez (1984). Additionally, all visual representations were done using R software (R Core Team 2024).

RESULTS AND DISCUSSION

Growth attributes: Plant height and dry matter accumulation showed non-significant differences among treatments during the early growth stage i.e. at 30 DAS. However, at 60 DAS, the T_6 treatment exhibited significantly higher plant height and dry matter accumulation compared to the other treatments, indicating a more robust growth response. As the crop advanced to 90 and 120 DAS, these differences became even more pronounced (Fig. 1). Notably, at 120 DAS, the T_6 treatment resulted in superior performance, achieving the highest plant height of 98 cm and dry matter accumulation of 1417 g/m². The T_4 treatment also recorded at par results to T_6 in terms of plant height and dry matter accumulation (Fig. 1). In contrast, the remaining treatments showed minimal variation in plant height, with non-significant differences from each other. However, the farmers' practice, T_9 , performed poorly in dry matter accumulation, recording 1092 g/m², and was statistically similar to T_1 and T_7 treatments. The variation in leaf area index (LAI) among different treatments was statistically non-significant during the initial crop growth stages (30 DAS and 45 DAS). However, from 60 DAS onwards, the studied treatments showed significant influence on the LAI of wheat. The T_6 treatment recorded the highest LAI, which was statistically at par with T_4 , while T_9 , T_7 and T_5 consistently showed the lowest LAI across the remaining stages. At 90 DAS, corresponding to the stage of maximum LAI for the crop, the T_6 treatment exhibited the highest LAI (4.98), closely followed by T_4 (4.87). In contrast, the lowest LAI was observed in T_7 (4.37), which was statistically similar to T_9 (4.39) (Fig. 2).

The higher growth parameters observed in the SSDF and SDF, such as improved LAI, plant height, and dry matter accumulation can be attributed to an optimized supply of water and nitrogen, coupled with improved soil conditions. These conditions comprise lower bulk density and higher porosity, which facilitate better root development, consistent with the findings of Patra *et al.* (2023a). Treatments with

75% RDN demonstrated consistently modest performance compared to those with 100% RDN. Among these, the T_5 treatment outperformed other 75% RDN treatments and also surpassed T_8 and T_9 , where wheat was sown in sequence with PTR practice. Additionally, the observed poor plant growth and performance from 30–60 DAS may be attributed to reduced metabolic and photosynthetic activity due to the lower temperatures during the December and January months of the growing season.

Crop phenology: The growth phases of crops are intently linked to yield, with pre and post-anthesis durations being crucial determinants of productivity. Therefore, accurately identifying and emphasizing phenological stages in field experiments is essential for understanding their impact on crop yield (Kumar *et al.* 2024a). In this study, the timing of anthesis and physiological maturity showed minimal variation among treatments (Table 1). Although results were statistically non-significant, all treatments with 75% RDN, except for T_5 (SSDF), experienced a delay in anthesis but reached physiological maturity earlier. This could be due to minor stress conditions, particularly related to nitrogen availability. This finding aligns with the established understanding that stress before anthesis extends the pre-anthesis phase, while stress during the post-anthesis period shortens it, as noted by Kumar *et al.* (2024b).

Yield attributes of wheat: The total number of spikes/m², spike length, number of grains/spike, spike weight, grain weight/spike and test weight of wheat varied significantly across different crop establishment techniques, irrigation methods and nitrogen doses. The T_6 treatment exhibited significantly higher values for spike length (10.14 cm), number of grains/spike (57.13), spike weight (3.59), grain weight/spike (2.95), and test weight (41.97) compared to other treatments (Table 1). The highest number of spikes/m² was recorded in the T_4 treatment (473.81), which was statistically similar to T_6 (465.55). Conversely, the lowest number of spikes/m² and spike length (9.37 cm) were observed in T_9 (369.0), although this was statistically

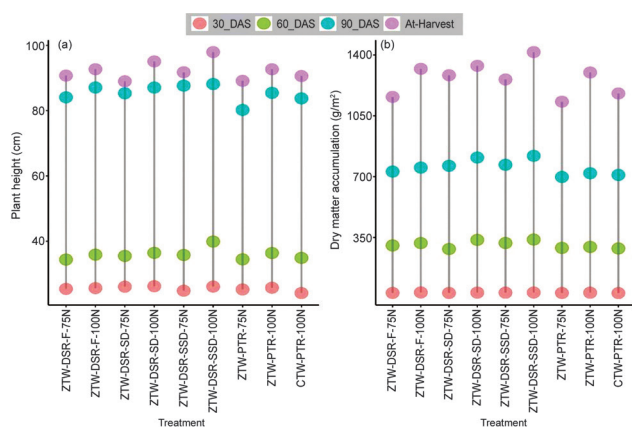


Fig. 1 Effect of different crop establishment techniques, irrigation methods, and nitrogen levels on (a) plant height and (b) dry matter accumulation of wheat (2-year mean basis). Treatment details are given under Materials and Methods.

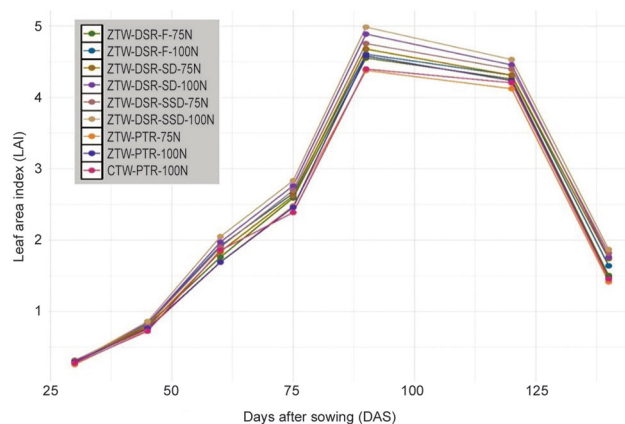


Fig. 2 Effect of different crop establishment techniques, irrigation methods, and nitrogen levels on leaf area index of wheat (2-year mean basis). Treatment details are given under Materials and Methods.

Table 1 Effect of different crop establishment techniques, irrigation methods, and nitrogen levels on phenology and yield attributes of wheat (2-year mean).

Treatment	Days to 50% anthesis	Days to physiological maturity	Spikes/m ²	Spike length (cm)	No. of grains/spike	Spike weight (g)	Grain weight/spike (g)	1000-Grain weight (g)
T ₁	88.76 ^a	138.43 ^a	379.25 ^{bc}	9.50 ^b	49.43 ^{bc}	2.90 ^b	2.24 ^{bc}	39.19 ^b
T ₂	87.22 ^a	136.75 ^a	405.00 ^{abc}	9.69 ^{ab}	51.60 ^{ab}	3.15 ^{ab}	2.62 ^{ab}	39.72 ^b
T ₃	88.01 ^a	139.49 ^a	410.04 ^{abc}	9.60 ^b	53.87 ^{ab}	2.97 ^b	2.43 ^{bc}	40.08 ^{ab}
T ₄	86.66 ^a	138.62 ^a	473.81 ^a	9.66 ^{ab}	54.53 ^{ab}	3.20 ^{ab}	2.60 ^{ab}	40.62 ^{ab}
T ₅	87.18 ^a	136.17 ^a	442.78 ^{abc}	9.83 ^{ab}	51.17 ^{abc}	3.13 ^b	2.50 ^{bc}	40.79 ^{ab}
T ₆	86.33 ^a	136.25 ^a	465.55 ^{ab}	10.14 ^a	57.13 ^a	3.59 ^a	2.95 ^a	41.97 ^a
T ₇	89.92 ^a	139.61 ^a	393.21 ^{abc}	9.71 ^{ab}	45.30 ^c	2.87 ^b	2.21 ^c	39.16 ^b
T ₈	87.17 ^a	138.83 ^a	404.01 ^{abc}	9.84 ^{ab}	49.80 ^{bc}	3.04 ^b	2.57 ^{abc}	39.60 ^b
T ₉	88.12 ^a	137.94 ^a	369.00 ^c	9.37 ^b	49.19 ^{bc}	2.93 ^b	2.23 ^c	39.25 ^b
SEm±	1.45	2.24	31.24	0.19	1.46	0.15	0.13	0.62
LSD (P=0.05)	NS	NS	93.67	0.56	4.37	0.44	0.38	1.87

Treatment details are given under Materials and Methods.

comparable to other treatments. Additionally, the T₇ treatment showed the lowest values for the number of grains/spike (45.30), spike weight (3.87), grain weight/spike (2.21), and test weight (39.16). These results confirm the findings of Kumar *et al.* (2024b) and align with the research by Parihar *et al.* (2017).

Yield of wheat: Different crop establishment techniques, irrigation methods, and nitrogen doses significantly influenced the grain, straw, and biological yields of wheat (Fig. 3). Among the treatments, T₆ realized the highest grain yield (5.96 t/ha), straw yield (8.67 t/ha) and biological yield (14.63 t/ha), superior to all other treatments due to enhanced source strength and yield attributes (Jat *et al.* 2019). The T₄ treatment also performed well, with significantly comparable results to T₆ in all three yield attributes. Conversely, the lowest yields were observed in the T₇ treatment, similar to the T₉ treatment. The grain and straw yield in the T₆ treatment were 24% and 22% higher, respectively, compared to the T₇ treatment, while the T₄ treatment showed 19% and 20% higher grain and straw yields, respectively, over T₇. The harvest index across treatments ranged from 39.64–40.75%, with no significant differences (data not presented).

The higher performance of the SDF and SSDF treatments can be attributed to several factors, improved synchronization of water and nutrient supply with crop demand, facilitating uniform delivery through a single system; reduced nitrogen losses due to runoff, leaching, and NH₃ volatilization, with enhanced soil retention of mineral nitrogen (Patra *et al.* 2023a); improved biochemical properties of the rhizosphere by altering nitrification, denitrification, and urease activity; and suppressed weed production, which may be further contributing to better nutrient use efficiency (Bhuiyan *et al.* 2023). These factors collectively enhance crop performance and lead to higher

yields. Consistent with these observations, meta-analyses by Bhuiyan *et al.* (2023) and Delbaz *et al.* (2023) reported an increase in the yield of upland crops by 62% and 20%, respectively, with subsurface and surface fertigation compared to traditional methods. Similarly, wheat yields were observed to be 5–10% higher in CA-based ZTW (T₁ and T₂) followed by DSR over CTW and ZTW followed by PTR (T₇, T₈, and T₉). This improvement can be attributed to increased carbon sequestration, better nutrient availability, enhanced soil moisture retention, and improved soil physical and biochemical properties. These findings align with the findings of Kumar *et al.* (2024a), Patra *et al.* (2023b) and Parihar *et al.* (2017).

Economics: Among the imposed treatments, ZTW-DSR-SSD-100N recorded the highest gross return (₹131,015)

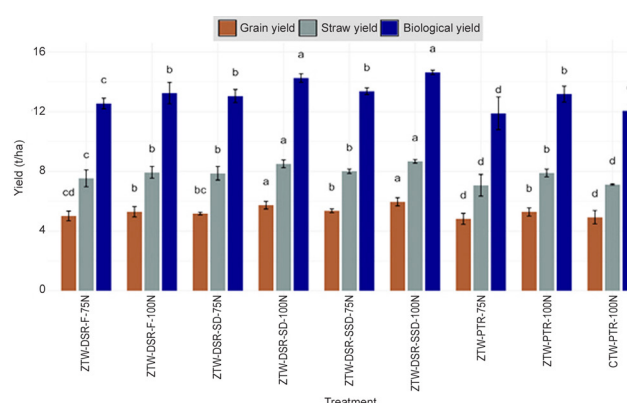


Fig. 3 Effect of different crop establishment techniques, irrigation methods, and nitrogen levels on grain, straw and biological yield of wheat (2-year mean).

Vertical bars indicate the standard error (SE) within each treatment.

Treatment details are given under Materials and Methods.

and net return (₹98,618), with the highest net BC ratio of 3.13, which is 8.5%, higher than the CTW-PTR-F-100N plots. The lowest gross and net returns were observed in the ZTW-PTR-75N, whereas lowest net BC ratio was observed in ZTW-DSR-SD-75N, because of additional cost incurred with installation of drip laterals (Supplementary Fig. 4). The performance of ZTW-DSR-F-100N and ZTW-PTR-F-100N was similar (3.13 and 3.08, respectively) and was superior to CTW-PTR-100N and ZTW-DSR-SD-100N (2.81 and 2.73, respectively). Overall, SSD with 100% RDN has been superior in economic performance of wheat coupled with CA.

Thus, our study concludes that layering of CA, and SSDF with 100% RDN technology can be recommended for farmers for better yield, efficient water and N management and economics of wheat under RW cropping system. While SDF showed comparable results, potential interference of drip laterals with tillage, harvesting, and intercultural operations may limit its adoption. The findings advocate for scaling the mentioned practices to achieve sustainable intensification of rice-based cropping systems in the eastern Indo-Gangatic Plains.

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