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Alternate crop establishment techniques in rice–wheat rotation influence wheat productivity, soil properties and profitability in eastern India

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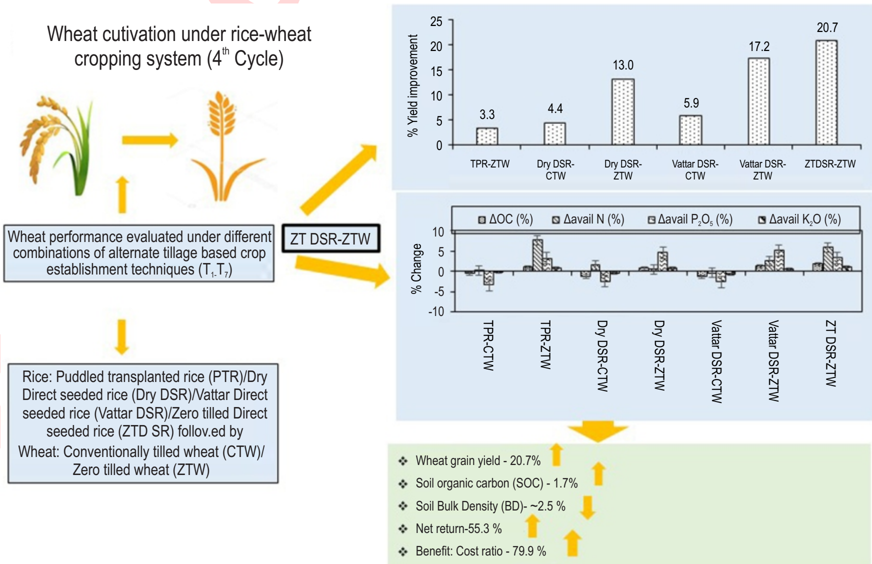
Abstract

Aim: To assess the impact of alternate tillage- based crop establishment against conventional technique in rice-wheat system on productivity, soil properties and profitability of wheat.

Methodology: Wheat was rotated with rice during *Rabi* 2023-24 (4th cycle) under an on-going field experiment, initiated during *Kharif* 2019, having six combinations of alternate tillage-based crop establishment techniques followed both in rice plus wheat and compared against the conventionally tilled rice-wheat cropping system. The treatments were allocated in randomized block design (RBD) having three replications. Yield parameters and grain yield of wheat were recorded along with soil properties and economics of wheat were estimated for each treatment.



Results: Wheat grain yield under zero tilled direct seeded rice- zero tilled wheat (ZTDSR-ZTW) was maximum and 13.0-20.7% higher ($p \leq 0.05$) over transplanted puddled rice-conventional tilled wheat (TPR-CTW). ZTW grown after vattar/dry direct seeded rice recorded higher positive balance (1.2-1.7%) in soil organic carbon and lower bulk density (~2.5%). ZTDSR-ZTW fetched the maximum increment in net return and B:C ratio for wheat (55.34 and 79.91%, respectively) over TPR-CTW.

Interpretation: The study indicates that in long run, ZTDSR-ZTW system, may serve as an alternate crop establishment technique for improving the productivity and profitability of wheat along with sustaining soil health in rice-wheat rotation.

Key words: Bulk density, Crop establishment techniques, Rice-wheat rotation, Zero-tilled wheat

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Introduction

The rice-wheat cropping system (RWCS) is the predominant food production system of entire south-east Asia, including India. It occupies an area of ~10.0 Mha (Jha *et al.,* 2023), contributing almost 75% (130 Mt of rice and 106 Mt of wheat) of the nation's cereal output and thus, playing a pivotal role in the food security and economy of India (Reddy *et al.,* 2025). In eastern India, RWCS is spread across the eastern Indo-Gangetic plains (IGP), mainlyin Bihar, covering 70% of gross cropped area and contributes about 77.4% of the total food grain production (Jha *et al.,* 2023). Both rice and wheat under the RWCS of this region are traditionally grown with intensive tillage operations,-rice as transplanted seedlings in puddled field followed by burning of rice residues and repeated tillage to prepare land for sowing of succeeding wheat (TPR-CTW). It leads to heavy consumption of water, fuel, labour and other resources. Therefore, despite the crucial role of RWCS in the country's food security, the resource intensiveness of this system, along with greenhouse gas (GHG) emission challenge its sustainability (Reddy *et al.,* 2025).

Around 80% of wheat produced in the region under RWCS faces the challenge of delayed sowing beyond the last week of November, exposing the crop to terminal heat during the anthesis to grain filling period (Sattar *et al.,* 2023), leading to poor seed setting and lower seed weight. Additionally, heavy puddling in rice and repetitive tillage in succeeding wheat leads to depletion of non-renewal resources like water, fuel and degrades soil structure plus soil organic matter (SOM) (Hoque *et al.,* 2025), resulting in soil compaction, poor input use efficiency (Bhatt *et al.,* 2016) and ultimately lower yield. Productivity of wheat in eastern IGP (Bihar) is about 14.3% below the national average (Directorate of Economics and Statistics 2024), whereas the projected demand of wheat in the country by 2050 is 140 million tonnes (McDonald *et al.,* 2022). This gap can be minimized by harnessing the optimum genetic potential of existing popular varieties of wheat through sustainable crop management practices, especially alternate tillage-based crop establishment (TCE) techniques like zero tillage (ZT), residue retention, moist (vattar)/ dry seeding in previous rice and/or succeeding wheat crop under rice-wheat system (Keil *et al.,* 2020), so that actual yield in farmers' field closely resembles the potential yield of a variety (Ahlawat *et al.,* 2025).

ZT technique is a type of alternate tillage, based on ecological approach when practiced in either rice or wheat or both the crop in the system. It improves wheat production by influencing several agronomic factors (Gathala *et al.,* 2013) at system level like lower or zero dependence on rain water for puddling of rice, leading to its timely establishment, improvement in soil physical properties, addition of soil organic matter through residue retention (Kumar *et al.,* 2018), reduced field operation for land preparations of wheat, resulting in timely (Erenstein and Laxmi,2008; Yadav *et al.,* 2021) and advanced sowing of wheat by 7-10 days (Kushwah *et al.,* 2020). This helps better germination of wheat due to lower mechanical resistance, conserved moisture and organic matter in soil,facilitating to escape terminal heat stress in wheat and ultimately improve its yield. Direct drilling of rice seeds in dry (Dry DSR) or pre-irrigated moist (Vattar DSR) soil after light tillage is one of the potential alternatives to transplanted puddled rice (TPR) which conserves water, soil, manual labour and energy in rice and gives added benefit to succeeding wheat, especially by better stand establishment and enabling timely sowing of wheat. Previous studies have reported 8% improvement in wheat yield after DSR than TPR (Yadav *et al.,* 2021). ZT have consistently demonstrated higher wheat yields, with increases ranging from 1–15% in the Northwest to 5.6–36% in the East across various studies in IGP (Malik *et al.,* 2004; Mishra *et al.,* 2021;Kandpal *et al.,* 2023).

Although some farm-level impact studies on Zero-tilled wheat (ZTW) focus on the western IGP, there is a significant lack of research in the Eastern IGP, where ZT is still relatively new (Erenstein and Laxmi, 2008). Alternate tillage-based crop establishment techniques used in wheat cultivation have not been adequately fine-tuned for local conditions (Reddy *et al.,* 2025), and there remains a significant gap in our understanding of the agronomic as well as soil attributes contributing towards a positive impact on wheat under the rice-wheat system. In this context, the present investigation aimed to assess the impact of alternate tillage- based crop establishment against conventional techniques on productivity, soil properties and profitability of wheat and to find out the key crop as well as soil attributes for such impact.

Materials and Methods

Experimental site: The field experiment was conducted at the research farm of Bihar Agricultural University, Sabour, Bhagalpur (25° 15'40" N latitude; 78° 2'45" E longitude, 45.75 m amsl) during the Rabi season, 2023-24. The wheat crop under the study was taken under on-ongoing research experiment in rice wheat system (4^{th} Cycle) initiated during kharif 2019-20. The climate of the area under study is sub-tropical in nature with rainfall mostly confined to monsoon months. Wheat experiences a cool, dry weather in the region, with a mean minimum temperature generally falling below 10°C during the coolest month-January. The weather scenario during the study period has been illustrated in Fig. 1. The maximum temperature ranged from 17 to 39°C, minimum temperature from 6 to 22°C with only 34.6 mm rainfall during *rabi* 2023-24. The soil of the experimental field was silty clay loam in texture and had a neutral to slightly alkaline reaction, medium in organic carbon, low in mineralizable nitrogen and medium in available phosphorus and potassium contents.

Experimental treatment details: The experiment was laid out in a randomized complete block design (RCBD) and replicated thrice with seven treatments consisting of T_1-Transplanted Puddled Rice-Conventional Tilled Wheat (TPR-CTW), T_2-Transplanted Puddled Rice-Zero Tilled Wheat (TPR-ZTW), T_3-Dry Direct-Seeded Rice-Conventional Tilled Wheat (Dry DSR-CTW), T_4- Dry Direct-Seeded Rice-Zero Tilled Wheat (Dry DSR-ZTW), T_5-Vattart Direct-Seeded Rice-Conventional Tilled Wheat

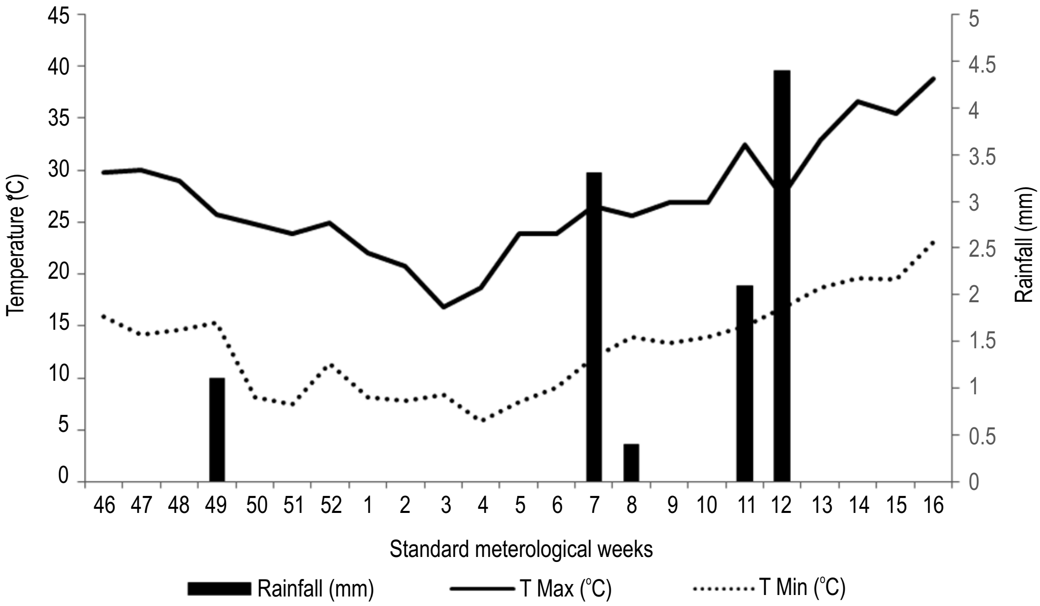

Fig. 1: Weekly weather condition during the cropping season (Rabi 2023-24).

(Vattar DSR-CTW), T_6-Vattar Direct-Seeded Rice-Zero Tilled Wheat (Vattar DSR-ZTW) and T_7- Zero Tilled Direct-Seeded Rice–Zero Tilled Wheat (ZT DSR–ZTW). The gross plot size was 4.4m x 40 m which could accommodate 11 rows of DSR (Dry/vattar/ZT) and wheat, spaced at 20 cm. Rice preceding the wheat crop under the study was either transplanted manually in a puddled field (TPR) with 20 ×15 cm spacing or directly seeded with zero-tilled fertilizer-cum-seed drill in a well-prepared dry levelled field (Dry- DSR) or in a well-prepared moist field prepared with a heavy pre-sowing irrigation followed by light tillage at optimum moisture (Vattar-DSR). Field preparation for TPR was made by repeated ploughing in bunded field having 2-3 cm of standing water till soft muddy consistency of soil was obtained, followed by one planking, while for DSR (Dry and Vattar) and CTW it was done by 2 cross ploughing followed by one harrowing and finally one planking. For ZTDSR and ZTW the crop seeds were drilled amidst 30 cm standing residues from ground of previous crop, two days after a pre-planting application of glyphosate (41%SL) @ 1.0 kg active ingredient ha^{-1}, to check the regrowth from stubbles of previous crops and flushes of weeds. Wheat variety HD 2967 was sown with a seed rate of 100 kg ha^{-1}, as per the sowing schedule given below:

	TPR followed by wheat	DSR (Dry/Vattar/ZT) followed by wheat
ZTW	30.11.2023	27.11.2023
CTW	06.12.2023	03.12.2023

Fertilizers were administered following the recommended dose, *i.e.,* 120:60:40 kg N: P_2O_5: K_2O ha^{-1}. One-third of the total N along with full amount of P and K fertilizers were applied during the final land preparation, *i.e.,* planking, using DAP, urea and MOP, in case of Dry/ Vattar DSR and CTW. The remaining amount of N fertilizer was applied in two equal halves, along with the first *i.e.,* 20 days after sowing (DAS) and the second (40 DAS) irrigation, using urea only. In case of ZTDSR, the basal fertilizer dose (One- third of the total N along with full amount of P and K) was drilled with the seed through zero-tilled fertilizer-cum-seed drill, using DAP, urea and MOP whereas the remaining amount of N fertilizer was top-dressed using urea as same as CTW.

Procedure for sampling and estimating yield attributes and yield: The plants from the border rows of each plot were deliberately eliminated to minimise the border effect. Therefore, the plant sample from 1 m^2 area of each plot was collected to estimate the spike density (number of spikes m^{-2}) and out of that, 10 randomly selected spikes were sampled to estimate number of grains per spike and weight of total grains obtained from those 10 spikes were converted into 1000 grain weight by multiplying with suitable factor. The produce from each net plot was harvested, sun dried till a constant weight (14% moisture) was attained, and threshed. The grains were cleaned and weighed after threshing. For obtaining grain yield, the weight of grains per net plot (g m^{-2}) was recorded treatment-wise from three replications, averaged and expressed as tonnes per hectare (t ha^{-1}).

Soil properties: As the wheat crop under the study was a part of the ongoing study on the rice-wheat system initiated during 2019-20, the soil chemical parameters were analysed treatment-wise before sowing as well as after crop harvest. Soil moisture was analysed before sowing, at flowering and grain filling stages. Soil bulk density was analysed only after crop harvest. All these analyses were performed following standard protocols. Soil bulk density and moisture content were determined by the core (cylinder) and gravimetric methods, respectively (Black et al., 1965). Soil pH and electrical conductivity were measured potentiometrically (Jackson, 1973). Soil organic carbon was estimated by the Walkley and Black method (Jackson, 1973). Available nitrogen was determined by the alkaline potassium permanganate ($KMnO_4$) method (Subbiah and Asija, 1956), available phosphorus by Olsen's method (Olsen *et al.*, 1954), and available potassium by the neutral ammonium acetate extraction method (Jackson, 1973), respectivily.

Economics of production

Cost of cultivation: The cost of cultivation was calculated separately for each treatment considering prices of inputs, labour wages per day and other expenses throughout the crop season and expressed as Rs. ha^{-1}.

Gross, net return and benefit cost ratio: Gross returns were calculated for each treatment by the conversion of the harvest (grain and straw) into monetary terms based on the current minimum support price (MSP) of grain and market price of straw and is given by the equation as follows:

$$\text{Gross return (Rs. ha}^{-1}) = \text{MSP of grain (Rs. kg}^{-1}) \times \text{grain yield (kg ha}^{-1}) + \text{Local market price of straw (Rs. kg}^{-1}) \times \text{straw yield (kg ha}^{-1})$$

The net return was calculated for each treatment by subtracting the cost of cultivation from the corresponding gross return for each treatment. Net return (Rs. ha^{-1}) = Gross return (Rs. ha^{-1}) - Cost of cultivation (Rs. ha^{-1}) Ultimately, the benefit cost ratio was estimated for each treatment by the formula given as

$$\text{Benefit cost ratio} = \frac{\text{Net return (Rs. ha}^{-1})}{\text{Total cost of cultivation (Rs. ha}^{-1})}$$

Statistical analysis: The data obtained from the field were subjected to statistical analysis using ANOVA for a RCBD design for the interpretation of results as described by Gomez and Gomez, (2010) with the help of Microsoft Excel and R software. Principal component analysis (PCA) was performed using Jamovi software (Version 2.6) (Jamovi Project, 2024).

Results and Discussion

The yield attributes of wheat,except 1000 grain weight, were significantly influenced by the alternate tillage and crop establishment (TCE) techniques (Table 1). The ZTDSR- ZTW treatment achieved maximum spike density m^{-2} (271) and grains $spike^{-1}$ (53.6), being at par with Dry DSR- ZTW (255 m^{-2} and 51.6, and Vattar DSR-ZTW (263 m^{-2} and 51.3, depicting an increment of 15.4-22.6 and 11.9-16.3%, respectively, over traditional TPR-CTW treatment. It is also clear that ZTW on an average produced 11.1 and 9.6% more spikes m^{-2} and grains $spike^{-1}$, respectively, than CTW. The impact of ZT on spike density of wheat was more pronounced (14.1 % increase) when practised after DSR (Dry/Vattar/ZT-DSR) than TPR. Higher spike density and grains $spike^{-1}$ in ZTW, especially after ZTDSR over TPR, may be attributed to improved physical condition of soil, leading to low soil compaction (Yadav *et al.,* 2021) which might have supported better crop establishment and subsequent tiller initiation, development and survival, nourishing large numbers of florets (data not given). These results are in line with the previous reports of Slafer *et al.,* 2014; Jat *et al.,* 2014; Mishra *et al.,* 2022. The 1000 grain weight was highest under TPR-ZTW (38.4g) while lowest under ZT DSR-ZTW (36.3g), however the differences were not significant. The 1000 grain weight of wheat may decrease as the number of grains increase. This reduction can be attributed to intra-competition for resources among grains for nutrients, water and photosynthates, leading to limited availability for individual grain filling (Acreche and Slafer, 2006; Philipp *et al.,* 2018; Vicentin *et al.,* 2024).

Grain yield of wheat was significantly influenced by the alternate tillage-based crop establishment techniques (Table 1). The grain yield was significantly highest under ZTDSR-ZTW (4.08 t ha^{-1}), being statistically comparable with Dry DSR-ZTW (3.82 kg ha^{-1}) and Vattar DSR-ZTW (3.96 t ha^{-1}), and higher than the remaining treatments, which ultimately resulted in 13.0-20.7 % yield improvement over TPR-CTW. Superiority of grain yield in ZTW after DSR (ZT/Dry/ Vattar) is due to better soil structure and soil aeration (Nandan *et al.,* 2018; Mishra *et al.,* 2022) which supported improvement in yield attributes like spike density and grains $spike^{-1}$. These results are also in agreement with the findings of Saurabh *et al.* (2021), who, also found that ZTW out performed CTW owing to higher soil quality index (SQI) under ZT based systems because of surface retention of residues of previous crop. The lowest grain yield was recorded under TPR-CTW (3.38 t ha^{-1}). Yield advantage under the remaining treatments over this traditional practice of TPR-CTW is shown in Fig. 2. It reflects that maximum yield advantage in ZTW was found when taken after ZTDSR (ZTDSR-ZTW-20.7%) followed by Vattar DSR-ZTW (17.2%) and Dry DSR-ZTW (13.0%) as compared to TPR-ZTW system. Higher grain yield of wheat under ZT can also be explained by the compound effects of earlier sowing, higher soil moisture availability owing to suppression of evaporation losses of soil water, reduced runoff loses, better soil physical properties, especially reduced bulk density, higher nutrient availability and uptake in comparison with CT (Leharwan *et al.,* 2023). The present study also depicts lower soil bulk density under ZT based systems which had positive impact on grain yield of ZTW (Table 2). After harvest of wheat (completion of the 4th rotation cycle) the soil bulk density was minimal under ZT DSR-ZTW (1.48 g cm^{-3}), being statistically at par with that of Vattar DSR-ZTW (1.52 g cm^{-3}) and Dry DSR-ZTW (1.53 g cm^{-3}) and significantly lower over the other treatments. In contrast, the highest bulk density was recorded under TPR-CTW (1.59g cm^{-3}). This reflects that ZTW established in plots having stubbles of previous DSR (ZT/Vattar/Dry) exhibited significantly lower BD and maximum reduction in BD over TPR-CTW was observed in ZT DSR-ZTW treatment (-2.52%). This is due to higher crop residues in ZT plots (Kumar *et al.,* 2024) which increase soil organic matter and porosity, resulting in higher soil volume per unit mass.

Table 1: Yield attributes and grain yield of wheat as affected by different crop establishment techniques under rice-wheat rotation

Treatments	Spike density (No. m^{-2})	No. of grains $spike^{-1}$	1000 grain weight (g)	Grain yield (t ha^{-1})
TPR-CTW	221	46.1	37.3	3.38
TPR-ZTW	226	47.4	38.4	3.49
Dry DSR-CTW	229	46.4	37.4	3.53
Dry DSR-ZTW	255	51.6	36.4	3.82
Vattar DSR-CTW	235	47.0	37.2	3.58
Vattar DSR-ZTW	263	51.3	36.5	3.96
ZT DSR-ZTW	271	53.6	36.3	4.08
SEm (±)	10.5	1.7	1.0	0.15
CD (P=0.05)	32.4	5.2	NS	0.47

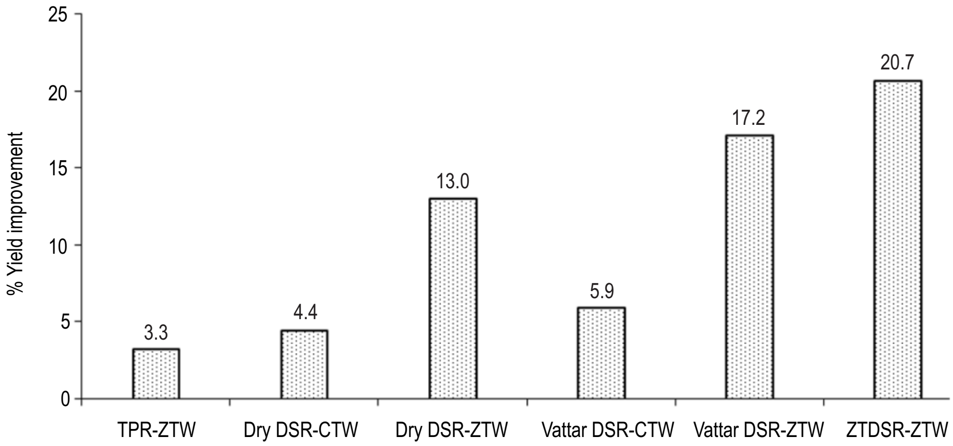

Fig. 2: Grain yield improvement (%) in wheat under different alternate crop establishment techniques over TPR-CTW.

Zero tillage-based systems also maintained steady soil moisture status in upper layer of the soil, preventing wheat from being exposed to abiotic stress, particularly terminal heat and drought stress during post-anthesis period and thus favoured grain yield. Periodic soil moisture content recorded before sowing (BS), at flowering (F) and grain filling (GF) stages showed maximum values under the treatment ZTDSR-ZTW (18.99, 16.31 and 21.30%, respectively) which were significantly superior over the remaining treatments (Table 2). Soil moisture content at GF, for all the treatments, was about 5-6% higher than that recorded at F, due to 6.5 mm ofrainfall received during the March 2^{nd} -3^{rd} week (Standard meteorological week 11 and 12, (Fig. 1). Soil moisture content under the ZTDSR-ZTW treatment at BS, F and GF stages was higher by 36.32, 49.36 and 29.74%, respectively, over TPR-CTW, due to reduced compaction and uniform distribution of macro-and micropores in soil, less evaporation losses due to surface residue, shielding direct sunlight and airflow over the surface soil (Korav *et al.,* 2024).

Superior yield performance of ZTW, especially after DSR may also be attributed to better health of soil in ZT based system, as evident from soil organic carbon (SOC) values before sowing as well as after harvest of wheat (Table 3,4). Before sowing of wheat (4^{th} cycle) significantly higher SOC was noticed under the ZTDSR-ZTW treatment (0.586%), being at par with that of ZTW taken in sequence with either Vattar DSR (0.568%) or Dry DSR (0.556%) or TPR (0.535%) (Table 3). Higher SOC under conservation tillage-based system, especially ZTDSR-ZTW, is attributed to minimal soil disturbances and anchored residues of previous crop which built up higher level of SOC in top layer of soil. Additionally, maintained soil moisture under ZT based systems (Table 2) also supported better microbial growth (data not given) which favoured improvement in SOC (Kumar *et al.,* 2018). It also depicts that rice establishment techniques did not have direct influence on soil organic carbon in succeeding wheat, though wheat established with ZT with the previous rice residues have significantly higher SOC than CT wheat where previous rice residues were removed. This is in agreement with the study of Kumar *et al.* (2024) where they found 23% higher SOC in the post-rainy crops (wheat/chickpea), directly sown under ZT with maintained residues of previous rice crop, and argued that this is due to less soil disturbance and addition of SOC via root biomass. Almost similar trend was recorded in case of SOC after harvest of wheat (Table 4). Better availability of soil nutrients like N, P_2O_5 and K_2O exerted positive influence on the performance of wheat under ZT based systems. Soil available N, P_2O_5 and K_2O before

Table 2: Soil bulk density and moisture content at different growth stages of wheat under different crop establishment techniques in rice-wheat rotation

Treatments	Bulk density ($g\ cm^{-3}$) after harvest	Soil moisture (%)		
		Before sowing	At flowering	At grain filling
TPR-CTW	1.59	13.93	10.92	16.34
TPR-ZTW	1.58	14.70	12.22	17.79
Dry DSR-CTW	1.55	11.73	11.21	15.70
Dry DSR-ZTW	1.53	13.56	12.56	18.17
Vattar DSR-CTW	1.54	12.49	11.13	16.11
Vattar DSR-ZTW	1.52	13.90	12.95	18.16
ZT DSR-ZTW	1.48	18.99	16.31	21.20
SEm (±)	0.02	0.86	0.59	0.62
CD (P=0.05)	0.05	2.64	1.82	1.91

Table 3: Soil chemical properties before sowing of wheat (4th cycle) as affected by different crop establishment techniques under rice-wheat rotation

	Soil chemical parameters before sowing					
Treatments	pH	EC ($dS\ m^{-1}$)	Organic carbon (%)	Available N ($kg\ ha^{-1}$)	Available P_2O_5 ($kg\ ha^{-1}$)	Available K_2O ($kg\ ha^{-1}$)
TPR-CTW	7.49	0.33	0.504	182.50	23.66	176.9
TPR-ZTW	7.47	0.32	0.535	184.27	25.8	184.2
Dry DSR-CTW	7.55	0.33	0.508	180.93	24.27	177.73
Dry DSR-ZTW	7.54	0.31	0.556	191.67	26.47	185.63
Vattar DSR-CTW	7.55	0.33	0.511	182.67	24.43	180.24
Vattar DSR-ZTW	7.53	0.29	0.568	189.33	26.13	186.33
ZT DSR-ZTW	7.45	0.28	0.586	214.17	33.6	191.47
SEm (±)	0.05	0.01	0.015	2.29	0.73	2.19
CD (P=0.05)	NS	NS	0.05	7.05	2.26	6.76

Table 4: Soil chemical properties after harvest of wheat (4th cycle) as affected by different crop establishment techniques under rice-wheat rotation

	Soil chemical parameters after harvest					
Treatments	pH	EC ($dS\ m^{-1}$)	Organic carbon (%)	Available N ($kg\ ha^{-1}$)	Available P_2O_5 ($kg\ ha^{-1}$)	Available K_2O ($kg\ ha^{-1}$)
TPR-CTW	7.50	0.32	0.501	182.67	22.86	176.43
TPR-ZTW	7.46	0.30	0.540	198.33	26.63	185.47
Dry DSR-CTW	7.56	0.32	0.502	183.70	23.68	177.07
Dry DSR-ZTW	7.53	0.3	0.560	191.67	27.67	186.9
Vattar DSR-CTW	7.56	0.32	0.504	181.90	23.80	178.83
Vattar DSR-ZTW	7.52	0.28	0.575	194.17	27.47	187.47
ZT DSR-ZTW	7.43	0.26	0.596	226.67	34.73	193.50
SEm (±)	0.05	0.01	0.016	3.19	0.68	2.22
CD (P=0.05)	NS	NS	0.050	9.82	2.1	6.83

sowing of wheat were estimated as maximum in ZTDSR-ZTW treatment, having significant superiority over rest of the treatments for N and P_2O_5, but at par inthe case of K_2O with Vattar/Dry DSR-ZTW (Table 3). After harvest of wheat the same soil chemical parameters were analysed and found similar trend (Table 4). It is evident from the comparison of values related to the soil parameters before sowing and after harvest of wheat (Fig. 3), that ZT wheat taken after Vattar/ZT DSR had distinctly higher positive gain in SOC (1.2 and 1.7%, respectively) as compared to other treatments. An almost similar trend was noticed for soil available P_2O_5 and K_2O having the maximum positive balance in either Vattar DSR-ZTW (5.1%) or ZT DSR-ZTW (1.1%) treatments, except for only soil available N where a lower positive balance was recorded under the above treatments than others. Similar positive gain in available phosphorous and potassium was also noticed by Yadav *et al.* (2021) in ZTW.

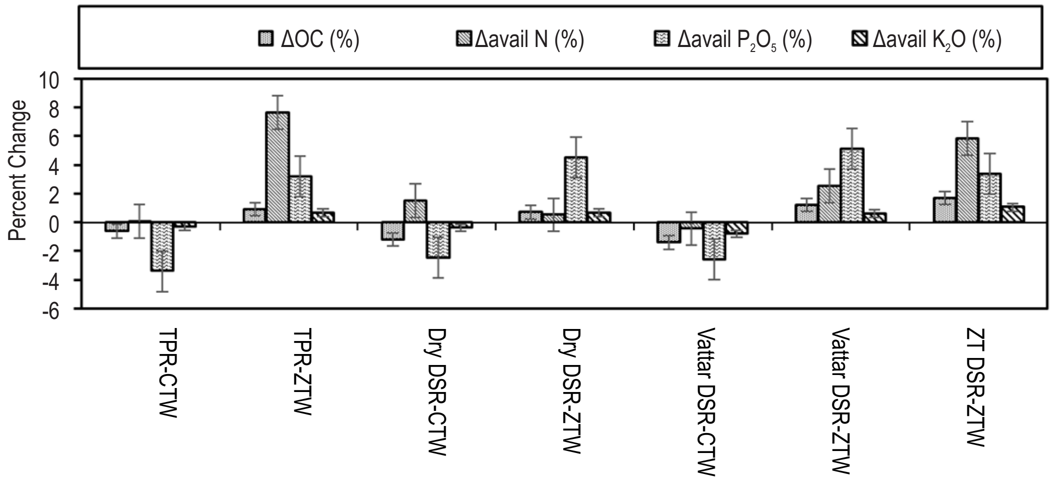

Fig. 3: Percent Change in soil chemical properties before and after sowing of wheat due to different alternate crop establishment techniques under 4th cycle of rice-wheat rotation.

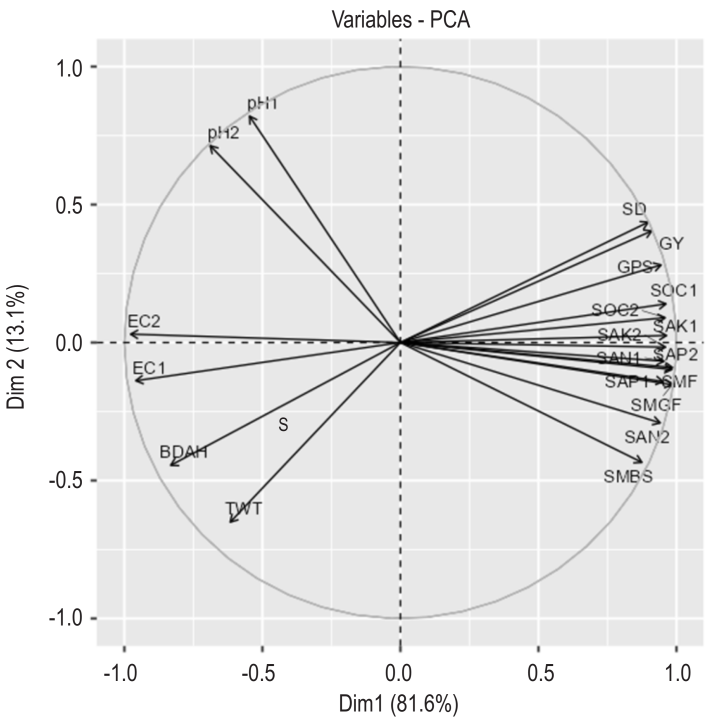

Fig. 4: Principal Component Analysis (PCA) for different response variables in wheat. SD= spike density; GPS= grains per spike; TWT= 1000 grain weight; GY= grain yield; pH, EC, SOC, SAN, SAP, SAK 1 and 2= soil pH, electrical conductivity, soil organic carbon, soil available N, soil available $P_2O_5$and soil available K_2O before and after sowing, respectively; BDAH= Bulk density after harvest; SMBS= soil moisture before sowing; SMF= soil moisture at flowering; SMGF=soil moisture at grain filling.

The PCA result indicated that spike density (SD) was the most influential trait affecting grain yield in wheat as evident from lowest acute angle between SD and GY (Fig. 4). Among the soil chemical parameters soil organic carbon (SOC) and soil available potassium (SAK) were found to play crucial role for controlling grain yield in wheat, depicting the importance of crop residue maintenance under ZT, which will add more organic matter to soil as well as release K to sustain yield. On the contrary, the soil bulk density was the key soil physical parameter having strong negative association with the GY of wheat.

Table 5: Effect of different crop establishment techniques on economics of wheat under rice-wheat rotation

Treatments	Total cost of cultivation (Rs ha^{-1})	Gross return (Rs ha^{-1})	Net return (Rs ha^{-1})	B:C ratio
TPR-CTW	41004	82297	41293	1.01
TPR-ZTW	35404	84961	49557	1.40
Dry DSR-CTW	41004	86097	45093	1.10
Dry DSR-ZTW	35404	93037	57633	1.63
Vattar DSR-CTW	41004	87352	46348	1.13
Vattar D DSR-ZTW	35404	96593	61189	1.73
ZT DSR-ZTW	35404	99551	64147	1.81
SEm (±)	-	3375	3375	0.09
CD (P=0.05)	-	10400	10400	0.28

Zero-tilled wheat showed a 15.8% decrement in cost of cultivation over the conventional tillage method (Table 5). Highest gross return, net return and B:C ratio was recorded for ZTDSR-ZTW (Rs.99551, 64147 ha^{-1} and 1.8) and was at par with Dry DSR-ZTW and Vattar DSR-ZTW, while the lowest was registered for TPR-CTW (Rs. 41293 ha^{-1} and 1.0). ZTDSR- ZTW reported 55.34% and 79.91% hike in the net return and B:C ratio, respectively over TPR-CTW. The net return and B:C ratio were higher under ZTW owing to increased grain and straw yields (data not given), along with a reduction in the cultivation cost. (Keil *et al.,* 2015; 2020), especially due to reduction in cost of intensive tillage operations (Laik *et al.,* 2014; Singh *et al.,* 2025).

It can be concluded that, after the 4th rotation cycle, full conservation tillage-based crop establishment system (ZTDSR-ZTW) fetched significantly higher grain yield due to improvement in yield attributes, especially number of spikes m^{-2}, higher soil organic carbon and reduced bulk density of soil. It also proved to be economical for wheat owing to reduced cost of cultivation and higher economic return. Thus, in the long run, rotating zero-tilled wheat with zero-tilled DSR may serve as a better alternative to the traditional intensive tillage-based rice-wheat system in the eastern India.

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