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RESEARCH ARTICLE

Impact of various crop establishment methods on soil organic carbon and nitrogen fractions in an alluvial soil

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Abstract

Adoption of conservation agriculture (CA) based crop establishment methods involving legumes enhances soil organic nitrogen and carbon fractions by promoting microbial activity and residue retention, thereby improving nutrient availability and crop productivity in alluvial soils. A field experiment was conducted at Bihar Agricultural University, Sabour, in 2023 to evaluate the effects of eight crop establishment methods combining DSR or transplanted puddled rice (TPR), followed by CTW (conventionally tilled wheat) or ZTW (zero tilled wheat) and Fallow (F) or Green Gram (GG). The treatments were laid out in a factorial randomized block design. Soil samples were analyzed for labile and stable SOC and organic and inorganic nitrogen fractions after the rice harvest. Results showed significant improvement in very labile carbon (29.34 %) and labile carbon (27.17 %) under Dry DSR-ZTW-GG (T4) over conventional TPR-CTW-F (T5). Similarly, T4 recorded the highest nitrate-N (31.91 mg kg^{-1}) and hydrolysable ammoniacal-N (149.53 mg kg^{-1}). The rice grain yield ranged from 4276.67 to 5193.33 kg ha^{-1}, with T8 (TPR-ZTW-GG) and T7 (TPR-CTW-GG) outperforming others, but statistically at par with T4. The rice yield was found to be strongly and positively correlated (p=0.01) with hydrolysable NH_4^+-N (r = 0.879), amino acid-N (r = 0.893), very labile carbon (r = 0.914) and labile carbon (r = 0.872), indicating that these fractions contribute the most towards yield performance. Integration of DSR, zero tillage wheat and legume in rotation significantly improves SOC and N dynamics while enhancing productivity, suggesting a promising alternative to conventional puddled rice systems which ultimately leads to sustainable alluvial soil management.

Keywords: crop establishment methods; nitrogen fractions; soil organic carbon fractions; soil health; sustainability; tillage practices

Introduction

Rice (*Oryza sativa L.*) is a staple crop that sustains approximately two-thirds of the global population (1), cultivated across 160 million hectares worldwide, with an annual production of about 700 million tons (2). In India, rice cultivation spans 47 million hectares, yielding around 135 million tons, with Bihar, situated in the Indo-Gangetic Plains (IGP), emerging as a key rice-producing region. Bihar benefits from favorable climatic conditions, including an annual rainfall of about 1200 mm and fertile loam to sandy loam soils that support rainfed rice cultivation. However, the predominant cultivation method in Bihar, puddling followed by transplanting (TPR), has garnered criticism for its environmental and economic drawbacks (2, 3). TPR is water-intensive, disrupts soil structure (2), accelerates organic matter decomposition and contributes to greenhouse gas emission, all of which results in a gradual decline in crop productivity, long-term soil fertility and environmental sustainability (4, 5).

To address these sustainability issues, alternative crop establishment techniques such as dry direct-seeded rice (Dry DSR) are gaining attention now-a-days. DSR reduces water use by 15-20 % (4), lowers labour and fuel costs (6), reduces methane and other green house gas emission (7), minimizes soil disturbance (8, 9) and improves soil structure. Previous researchers (10) found that CA practices (DSR-ZTW with residue retention) enhanced water productivity by 25-35 % and reduced production costs by ~15 %. Former researchers observed improved wheat yields in residue-retained CA systems compared to residue-removed plots under water-limited conditions (11). Previous studies demonstrated a ~40 % reduction in greenhouse gas (GHG) emissions in DSR-ZT systems with residue management, contributing to climate-smart agriculture goals (12) .

Soil organic carbon (SOC) and nitrogen (N), primarily derived from the decomposition of plant and animal residues, are critical components of soil health and crop productivity. SOC, primarily derived from the decomposition of plant and animal residues, plays a pivotal role in nutrient cycling, soil structure and water retention. Additionally, SOC contributes significantly to climate change mitigation through carbon sequestration (13). As studies have shown, unsustainable farming practices, including the traditional TPR method, lead to a decline in SOC, highlighting the need for effective soil management strategies (14). The amount and distribution of SOC in soil are influenced by several factors such as soil properties, agricultural practices and environmental conditions (15). SOC is categorized into two primary fractions: stable and labile carbon. The stable or recalcitrant fraction, resistant to decomposition, contributes to nutrient cycling, long-term carbon sequestration, labile SOC is sensitive to land management practices (16) thus making it a valuable indicator of soil quality. Soil organic nitrogen (SON) constitutes about 90 % of the total nitrogen and includes various forms, such as hydrolysable ammoniacal nitrogen (HAN), amino acid N (AAN), amino sugar N (ASN) and non-hydrolysable N (NHN), all of which result from the decomposition of organic matter (17). Inorganic nitrogen, in the form of nitrate (NO_3^-) and ammonium (NH_4^+), is readily available to plants and plays a key role in promoting crop growth. The mineralization of organic nitrogen into inorganic forms is central to nutrient availability in soils and is a key factor influencing crop productivity (18). Sustainable management practices that enhance functional SOC and N fractions can directly influence yield, soil fertility and environmental resilience (19).

Despite the recent research advancements mentioned above, few areas still remain unexplored. Very few literatures till date have dealt with the effect of CA based crop establishment methods on soil carbon and nitrogen fractions specifically in eastern alluvial soil. Moreover, most of the previous literatures have reported the short-term result of CA practice. Our experiment provides novelty in this matter too as the data shared in this paper showcases the effect after 4 years of adoption of CA based crop establishment methods. Association of various C and N fractions with crop yield in terms of correlation matrix have also been seldom documented. Different rice crop establishment methods, such as TPR and DSR, can affect the cycling of carbon and nitrogen, thereby influencing nutrient availability and soil health. Understanding these interactions is essential for identifying practices that promote sustainable soil fertility and improve rice yield.

To address this gap, a study titled “Impact of Various Crop Establishment Methods on Soil Organic Carbon and Nitrogen Fractions of an Alluvial Soil” was conducted at the experimental farm of Bihar Agricultural University, Sabour. The particular objective of this study was to evaluate the impact of various rice crop establishment methods on SOC and N fractions in alluvial soils. The findings of this study aim to contribute to the development of sustainable rice farming practices that enhance soil health, improve nutrient cycling and increase agricultural productivity in Bihar’s rice-wheat systems.

Materials and Methods

Experimental site

A field experiment was carried out at the research farm of Bihar agricultural University, Sabour, Bhagalpur (24°13'45" N, 87°02'55" E, 25 m above sea level) in Bihar, Eastern India, during the *Kharif* season of 2023. This study, which began in 2019, forms part of a long-term rice-wheat cropping system. The soil at the site is silt loam, consisting of 34 % sand, 50 % silt and 16 % clay. At the start of the study, the soil had a neutral pH of 7.45, was non-saline (0.28 dS m^{-1}), with a moderate soil organic carbon (SOC) content of 5.47 mg g^{-1}. The soil also had low available nitrogen (195.15 kg ha^{-1}), medium available potassium (178.34 kg ha^{-1}) and medium available phosphorus (26.42 kg ha^{-1}). The region experiences a tropical to subtropical climate, receiving an annual rainfall of 1376 mm, most of which occurs during the wet season (mid-June to mid-October).

Experimental design and treatments

The experiment was designed using a factorial randomized block design (factorial RBD) with eight treatments combinations, each replicated three times and conducted in plots measuring 176 m^2 (40.0 m x 4.4 m). The treatments included various combinations of crop establishment methods. The specific details of the treatments are provided in Table 1. The layout of the experimental field has been shown on Fig. 1.

The treatment combinations were selected to represent a range of crop establishment scenarios relevant to conservation agriculture. Direct-seeded rice (DSR), along with zero-tillage wheat (ZTW), offer reduced soil disturbance and better residue retention compared to conventional systems. Green gram was incorporated in one treatment to evaluate the role of short-duration legumes in biological nitrogen fixation and organic matter enrichment. This factorial setup allows a comprehensive assessment of how tillage, residue and cropping intensity interact to influence SOC and nitrogen fractions in alluvial soils.

Field preparation and crop management

Before laying out the experiment, the land was plowed twice with disc plough and cultivator followed by planking to break the clods for pulverized bed. A 1 m irrigation channel was also made. Dry DSR plots were sown by sowing pre-treated seeds of rice variety Bina Dhan-11 on 11-12 July 2023. Rice seeds were treated with Bavistin @ 2 g kg^{-1} before sowing to control seedborne pathogens. TPR plots involved raising a nursery on 9 July 2023, with transplanting carried out between 5-7 August 2023 at a spacing of 20 cm × 10 cm.

For fertilization, a uniform recommended dose of 150 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1} was applied. Phosphorus and potassium were applied as a basal dose using diammonium phosphate (DAP) and muriate of potash (MOP), while nitrogen was applied in three splits using urea: 50 % basal, 25 % at active tillering and 25 % at panicle initiation.

Irrigation was provided as per crop requirement and weed control was done manually and with pre-emergence herbicides as per the package of practices. Green gram (*Vigna radiata*) was sown as a summer legume before rice and incorporated into the

Table 1. Treatment details of experimental plot

Treatment connotation	Treatment details
T_1	Dry Direct Seeded Rice- conventional Tillage Wheat-Fallow (Dry DSR-CTW-F)
T_2	Dry Direct Seeded Rice - Zero Tillage Wheat – Fallow (Dry DSR-ZTW-F)
T_3	Dry Direct Seeded Rice- conventional Tillage Wheat-Green gram (Dry DSR-CTW-GG)
T_4	Dry Direct Seeded Rice-Zero Tillage Wheat-Green gram (Dry DSR-ZTW-GG)
T_5	Transplanted Puddled Rice-Conventional Tillage Wheat-Fallow (TPR-CTW-F)
T_6	Transplanted Puddled Rice-Zero Tillage Wheat-Fallow (TPR-ZTW-F)
T_7	Transplanted Puddled Rice-Conventional Tillage Wheat-Green gram (TPR-CTW-GG)
T_8	Transplanted Puddled Rice-Zero Tillage Wheat-Green gram (TPR-ZTW-GG)

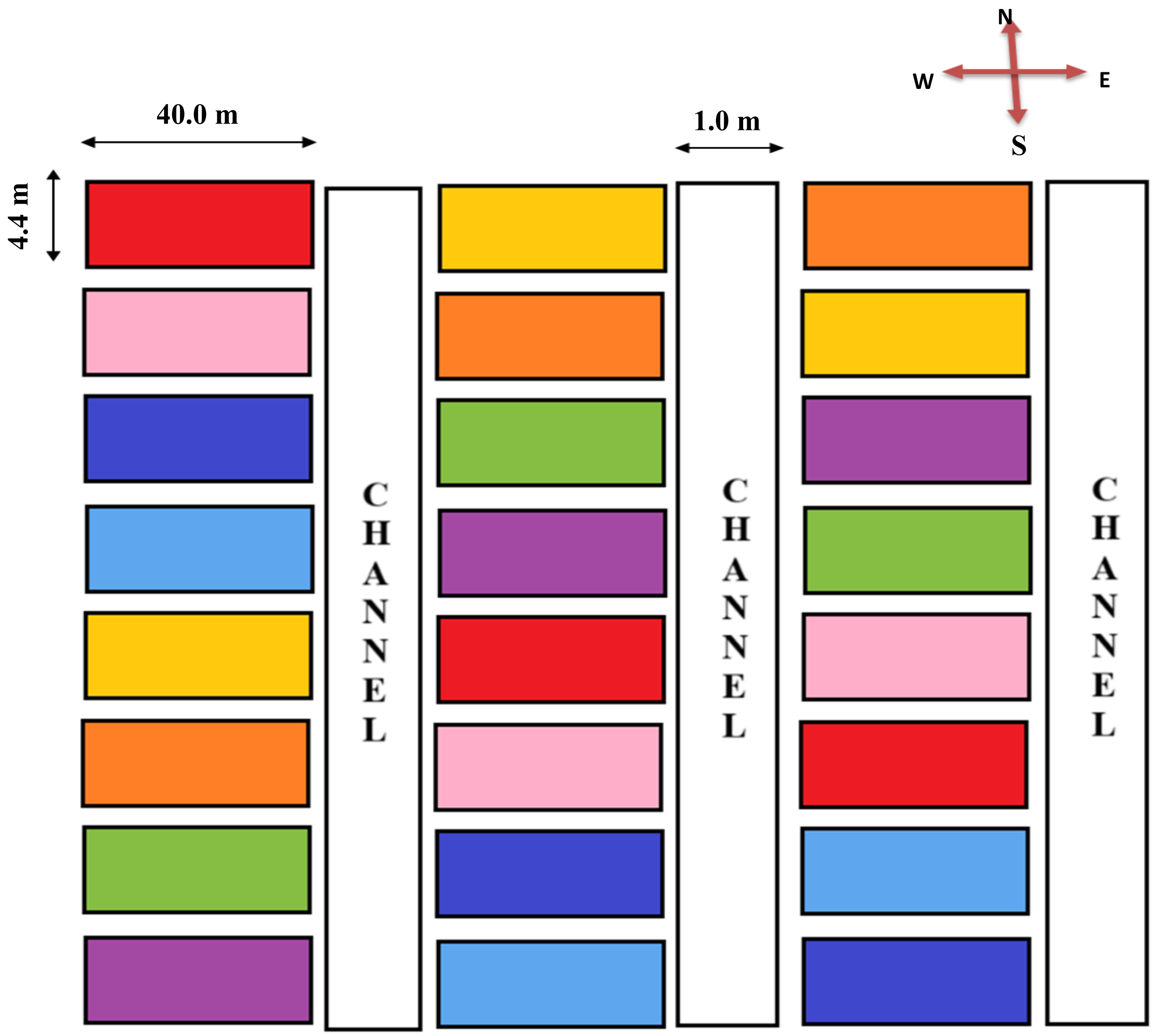

Fig. 1. Layout of experimental field.

soil at flowering stage. Rice was harvested on 9 November 2023. Post-harvest, soil samples were collected for analysis of carbon and nitrogen fractions.

Soil sampling and analysis

Soil samples were collected from 0-15 cm depth after rice harvest, using a screw auger at 5-6 spots per plot and composited following the rice harvest. A portion of the fresh samples were refrigerated for analysis of inorganic nitrogen fractions (nitrate and ammoniacal N) using 2M KCl extraction method given in previous studies (20) and organic nitrogen fractions using acid hydrolysis method (21), while the rest were processed for determination of carbon fractions (22) and total carbon by modified wet oxidation method (23).

Statistical analysis

The data collected from the field were analyzed using "Analysis of Variance" (ANOVA) in factorial RBD using the excel sheet data analysis tool pack (Microsoft Corporation, USA). To compare the difference between the treatment means, the least significant difference (LSD) at the 5 % level of significance and the standard error of mean (Sem ±) were calculated for each character and included in the summary tables of the results. Duncan's Multiple Range Test (DMRT) was performed to adjudge differences among treatment means (24). After this Pearson correlation matrix was calculated among the different parameters using SPSS window version 16.0 (SPSS Inc., Chicago, IL, USA).

Results

Carbon dynamics in soil after rice harvest.

The distribution of soil organic carbon fractions varied significantly across treatments (Table 2). Very labile carbon (VLC) and labile carbon (LC) were significantly influenced ($p \leq 0.05$) by the crop establishment methods and legume integration. Treatments with green gram inclusion and zero tillage wheat (ZTW) consistently recorded higher levels of VLC and LC. The highest VLC was observed in T4 (Dry DSR-ZTW-GG) at 2.48 g kg^{-1}, followed closely by T8 (TPR-ZTW-GG) at 2.39 g kg^{-1}, both significantly higher than the treatment T5 (TPR-CTW-F) (1.92 g kg^{-1}) which is usually followed by majority of the farmers in this area. A similar trend was observed for LC, with T4 and T8 recording 1.86 and 1.77 g kg^{-1}, respectively, compared to 1.46 g kg^{-1} in T5. The percentage change in various fractions with respect to T5 has been shown in Fig. 2. While the less labile carbon (LLC), non-labile carbon (NLC) and total SOC fractions showed numerically higher values in treatments with legumes and ZTW, the differences were statistically non-significant. This suggests that short-term changes in carbon dynamics are more pronounced in

Table 2. Effect of various rice crop establishment methods on soil carbon fractions in g kg^{-1}

Treatment	Very labile C (g kg^{-1})	Labile C (g kg^{-1})	Less Labile C (g kg^{-1})	Non-Labile C (g kg^{-1})	Total C (g kg^{-1})
T_1: Dry DSR-CTW-F	1.87d	1.41e	3.01	6.31	12.60
T_2: Dry DSR-ZTW-F	2.21ab	1.57cde	3.13	6.75	13.67
T_3: Dry DSR-CTW-GG	2.32ab	1.70abc	3.26	7.11	14.40
T_4: Dry DSR-ZTW-GG	2.48a	1.86a	3.46	7.24	14.90
T_5: TPR-CTW-F	1.92cd	1.46e	3.03	6.59	13.00
T_6: TPR-ZTW-F	2.18bc	1.51de	3.07	6.70	13.47
T_7: TPR-CTW-GG	2.26ab	1.66bcd	3.22	7.10	14.33
T_8: TPR-ZTW-GG	2.39ab	1.77ab	3.38	7.19	14.78
Sem ±	**0.09**	**0.05**	**0.11**	**0.61**	**0.63**
C.D. (P ≤ 0.05)	**0.26**	**0.16**	**NS**	**NS**	**NS**

Different letters denote significant differences among treatment means according to Duncan's Multiple Range Test (DMRT) at p<0.05

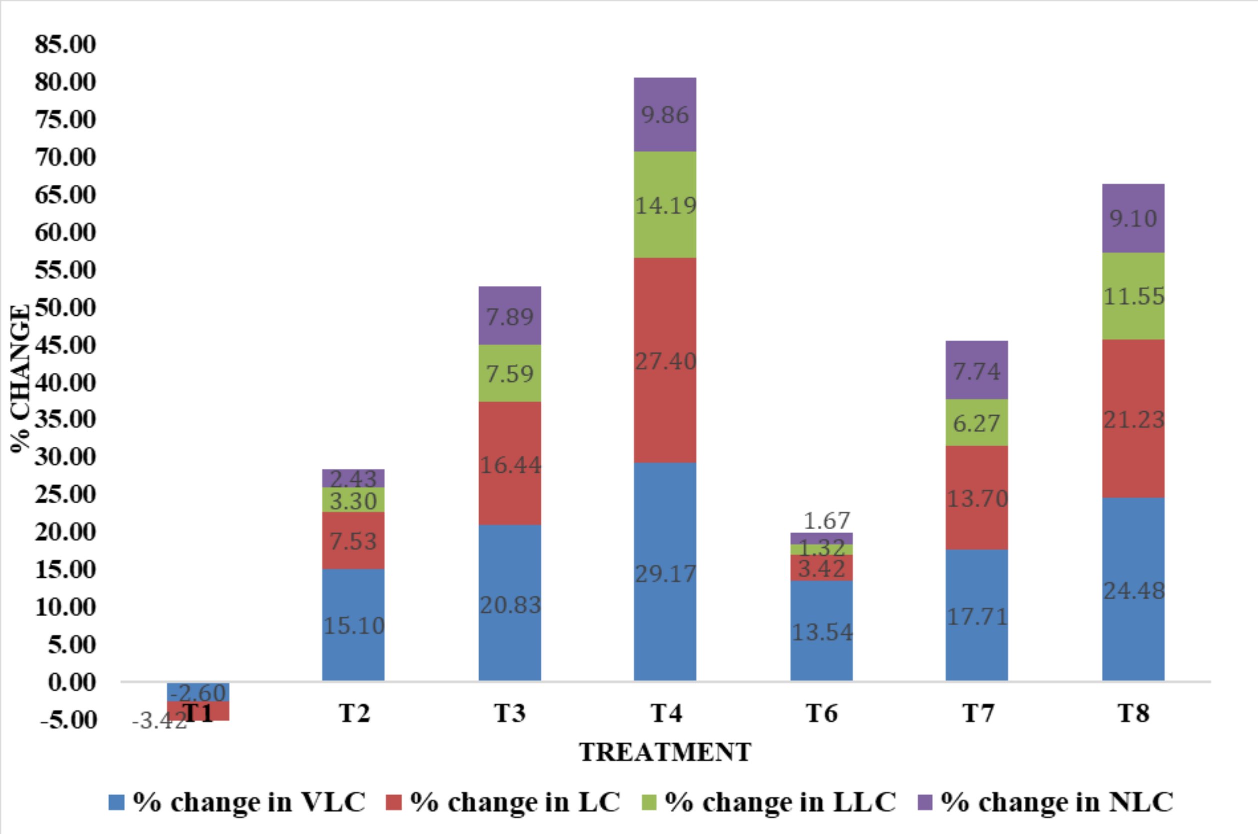

Fig. 2. Percent increase or decrease in carbon pools w r t TPR-CTW-F (T5)

the active SOC pools (VLC and LC), which are more sensitive to recent organic inputs and management interventions. Overall, the results highlight that Dry DSR and TPR systems supplemented with zero tillage and green gram residues significantly enhance the most biologically active carbon pools in soil, indicating a positive shift in soil health and short-term carbon cycling.

Nitrogen dynamics in soil after rice harvest

Inorganic nitrogen fractions

Significant differences ($p \leq 0.05$) were observed in nitrate-N (NO_3^--N) and ammoniacal-N (NH_4^+–N) concentrations across treatments, while variations in total inorganic N were statistically non-significant ($p > 0.05$) (Table 3). The highest nitrate-N content was recorded under T4 (Dry DSR-ZTW-GG) at 31.91 mg kg^{-1}, which was statistically at par with T3 (30.37 mg kg^{-1}), T8 (28.27 mg kg^{-1}) and T7 (27.80 mg kg^{-1}). These treatments involved either Dry DSR, green gram inclusion, or both, suggesting that aerobic soil conditions and nitrogen-rich legume residues favoured nitrification. In contrast, the lowest NO_3^-–N values were observed in TPR-based and fallow treatments (T1, T5, T6), ranging from 22.83 to 23.87 mg kg^{-1}, likely due to anaerobic conditions under puddling, which are less conducive to nitrifier activity.

Ammoniacal-N levels were highest in T8 (62.73 mg kg^{-1}) and T7 (60.94 mg kg^{-1}), both TPR-based systems with green gram and were significantly greater than the lowest group represented by T1 and T2. This trend indicates that legume inclusion boosted organic N mineralization, thereby enhancing NH_4^+–N accumulation. The percentage change in both fractions with respect to the traditionally followed practice (T5) has been shown in Fig. 3.

Although total inorganic N followed a similar trend to individual fractions, the differences were not statistically significant. Numerically, the highest total-N (inorganic-N + organic-N) was recorded in T4 (1008.77 mg kg^{-1}) and T8 (1000.11 mg kg^{-1}), reinforcing the synergistic benefits of zero tillage and legume integration on soil N availability.

Organic nitrogen fractions

The crop establishment methods significantly influenced key organic nitrogen fractions, reflecting changes in soil N dynamics under varying tillage and residue management practices (Table 4).

Table 3. Effect of various rice crop establishment methods on soil inorganic nitrogen fractions in mg kg^{-1}

Treatment	NO_3^-–N (mg kg^{-1})	NH_4^+–N (mg kg^{-1})	Total-N (Inorg. + Org.) (mg kg^{-1})
T_1: Dry DSR-CTW-F	23.87b	46.98b	898.97
T_2: Dry DSR-ZTW-F	27.00ab	48.40b	932.45
T_3: Dry DSR-CTW-GG	30.37a	57.17ab	978.70
T_4: Dry DSR-ZTW-GG	31.91a	57.58ab	1008.77
T_5: TPR-CTW-F	22.83b	55.01ab	886.84
T_6: TPR-ZTW-F	22.97b	55.54ab	918.84
T_7: TPR-CTW-GG	27.80ab	60.94a	967.00
T_8: TPR-ZTW-GG	28.27ab	62.73a	1000.11
Sem ±	**1.80**	**3.19**	**27.99**
C.D. ($P \leq 0.05$)	**5.47**	**9.66**	**NS**

Different letters denote significant differences among treatment means according to Duncan's Multiple Range Test (DMRT) at $p<0.05$

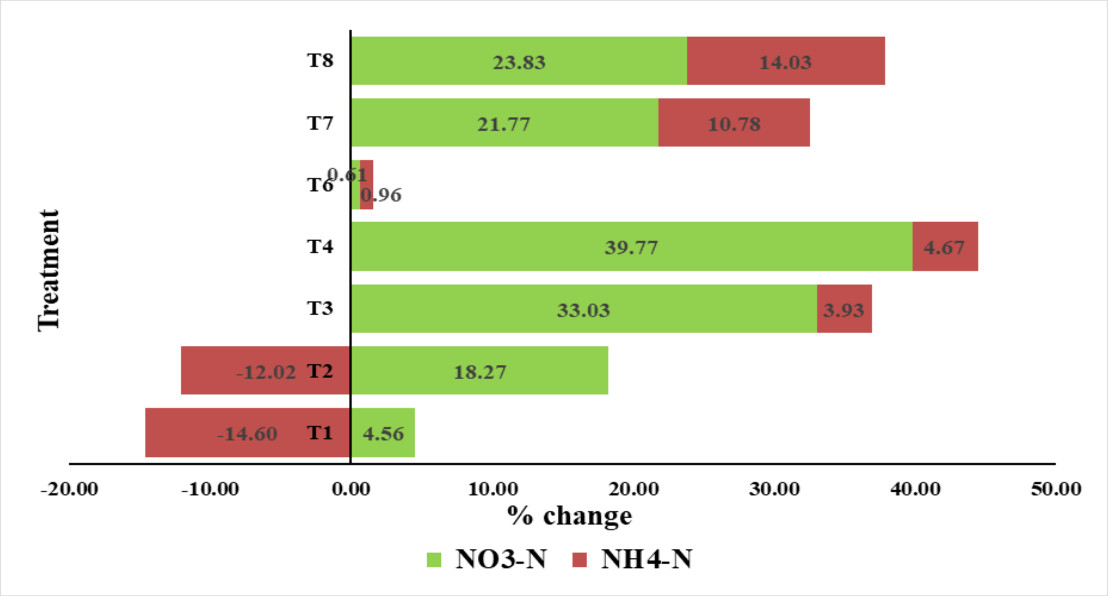

Fig. 3. Percent increase or decrease in NO3-N & NH_4^+-N w r t TPR-CTW-F (T5).

Total hydrolysable nitrogen (TH-N) ranged from 623.00 to 698.87 mg kg^{-1}, with the highest value under Dry DSR-ZTW-GG (T4), though the variation was statistically non-significant. However, hydrolysable NH_4^+-N (HAN), amino acid-N (AAN) and amino sugar-N (ASN) showed significant differences, with T4 consistently recording the highest values, statistically at par with T8 and T3. T4, T3 and T8 resulted in 19.24 %, 11.88 % and 17.04 % increment in HAN respectively over the conventional practice i.e. T5. The enhanced labile nitrogen pools under ZTW and green gram residue incorporation suggest improved microbial activity and nitrogen mineralization potential, likely due to better soil organic matter quality and reduced disturbance. AAN and ASN, which are sensitive indicators of organic matter turnover, were substantially higher in T4, T8 and T3, validating the hypothesis that conservation agriculture practices enhance nitrogen cycling efficiency. The percentage change of three major organic-N fractions (HAN, AAN and ASN) with respect to the traditionally followed practice (T5) has been shown in Fig. 4. In contrast, unidentified-N (UN) and non-hydrolysable-N (NHN) did not differ significantly, indicating that the more stable nitrogen pools respond slowly to short-term management changes. Overall, the results underscore the positive influence of zero tillage and legume residue incorporation on enhancing the labile organic nitrogen fractions, there by supporting long-term soil fertility and sustainability in alluvial soils.

Rice yield performance

Grain and straw yield varied significantly across the different crop establishment treatments (Table 5). The highest grain yield was recorded in T8 (TPR-ZTW-GG) at 5193.33 kg ha^{-1}, followed by T7 (TPR-

Table 4. Effect of various rice crop establishment methods on soil organic nitrogen fractions in mg kg^{-1}

Treatment	Total Hydrolysable-N (mg kg^{-1})	Hydrolysable NH4$^+$-N (mg kg^{-1})	Amino Acid –N (mg kg^{-1})	Amino Sugar-N (mg kg^{-1})	Unidentified-N (mg kg^{-1})	Non-Hydrolysable -N (mg kg^{-1})
T_1: Dry DSR-CTW-F	634.57	128.77b	288.53bc	48.67c	168.60	193.55
T_2: Dry DSR-ZTW-F	651.93	134.80ab	318.33ab	49.33c	149.47	205.11
T_3: Dry DSR-CTW-GG	673.07	140.30ab	327.33a	53.00abc	152.43	218.10
T_4: Dry DSR-ZTW-GG	698.87	149.53a	346.00a	57.33a	146.00	220.42
T_5: TPR-CTW-F	623.00	125.40b	275.00c	48.00c	174.60	186.00
T_6: TPR-ZTW-F	642.67	131.03b	291.67bc	49.00c	170.97	197.67
T_7: TPR-CTW-GG	664.00	135.90ab	319.67ab	50.67bc	157.77	214.26
T_8: TPR-ZTW-GG	688.70	146.77a	334.33a	55.33ab	152.27	220.41
Sem ±	**20.10**	**4.64**	**9.70**	**1.71**	**16.89**	**13.58**
C.D. ($P \leq 0.05$)	**NS**	**14.07**	**29.42**	**5.19**	**NS**	**NS**

Different letters denote significant differences among treatment means according to Duncan's Multiple Range Test (DMRT) at $p<0.05$

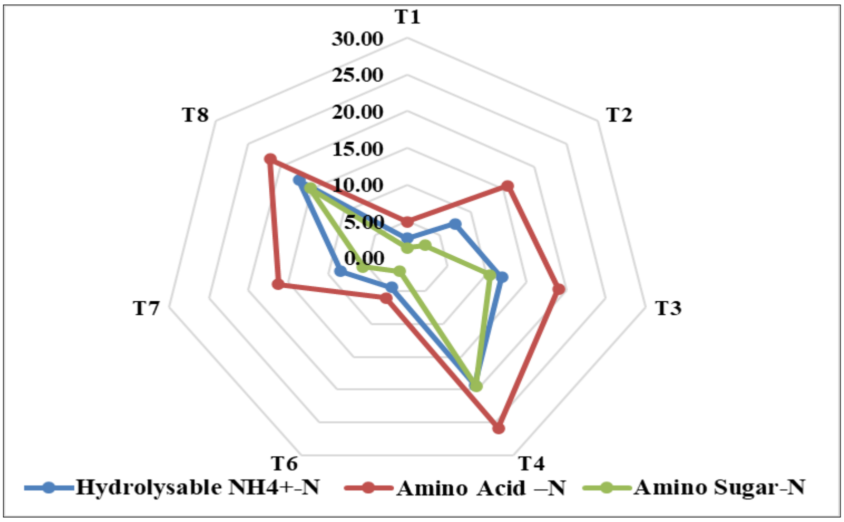

Fig. 4. Percent increase or decrease in HAN, AAN and ASN w r t TPR-CTW-F (T5).

CTW-GG) at 5060.00 kg ha^{-1} and T4 (Dry DSR-ZTW-GG) at 4753.33 kg ha^{-1}. The lowest yield was observed in T1 (Dry DSR-CTW-F) at 4276.67 kg ha$_{-1}$. Straw yield followed a similar trend, with T8 producing the maximum (6660.00 kg ha^{-1}) and T1 the minimum (5444.33 kg ha^{-1}). Treatments that included green gram (T3, T4, T7, T8) consistently showed higher yields than their fallow counterparts, highlighting the beneficial effects of legume integration. Statistical analysis revealed significant differences in both grain and straw yields at the 5 % probability level, confirming the influence of combined establishment practices on productivity.

Correlation study

Pearson's correlation analysis was carried out to determine the relationships among SOC and nitrogen fractions (Table 6). Analysis of the data revealed strong and significant positive correlations among labile nitrogen fractions (HAN, AAN, ASN) and labile carbon pools (VLC, LC, LLC), indicating synchronized turnover of carbon and nitrogen under residue-retentive treatments. The rice yield was found to be strongly and positively correlated (p=0.01) with HAN (r = 0.879), AAN (r = 0.893), VLC (r = 0.914) and LC (r = 0.872), indicating that these fractions contribute the most towards the nutrient enrichment and subsequent yield performance. It is also noteworthy that as per our hypothesis, the Dry DSR-ZTW-GG (T4) resulted in highest numerical value of the above-mentioned fractions which is ultimately reflected in the yield.

Discussion

The study explores how contrasting crop establishment methods encompassing combinations of tillage intensity (conventional and

Table 5. Effect of rice crop establishment methods on rice grain and straw yield (kg ha^{-1})

Treatment	Grain Yield (kg ha^{-1})	Straw Yield (kg ha^{-1})
T_1: Dry DSR-CTW-F	4276.67c	5444.33bc
T_2: Dry DSR-ZTW-F	4353.33c	5350.00c
T_3: Dry DSR-CTW-GG	4586.67bc	5993.33abc
T_4: Dry DSR-ZTW-GG	4753.33abc	6126.67ab
T_5: TPR-CTW-F	4590.00bc	6090.00ab
T_6: TPR-ZTW-F	4653.33bc	6116.67ab
T_7: TPR-CTW-GG	5060.00ab	6533.33a
T_8: TPR-ZTW-GG	5193.33a	6660.00a
Sem±	**172.14**	**238.74**
C.D. (P ≤ 0.05)	**522.13**	**724.13**

Table 6. Pearson correlation among SOC and N fractions

	NO_3-N	NH_4^+-N	HAN	AAN	ASN	UN	NHN	VLC	LC	LLC	NLC	Grain yield
NO_3-N	1											
NH_4^+-N	0.442*	1										
HAN	0.899**	0.573**	1									
AAN	0.952**	0.493*	0.960**	1								
ASN	0.871**	0.596**	0.976**	0.893**	1							
UN	-0.922	-0.274	-0.864	-0.956	-0.769	1						
NHN	0.922**	0.623**	0.934**	0.970**	0.869**	-0.882	1					
VLC	0.855**	0.654**	0.926**	0.931**	0.864**	-0.835	0.930**	1				
LC	0.924**	0.681**	0.968**	0.950**	0.951**	-0.847	0.938**	0.953**	1			
LLC	0.904**	0.670**	0.982**	0.942**	0.975**	-0.831	0.924**	0.928**	0.992**	1		
NLC	0.855**	0.812**	0.873**	0.880**	0.841**	-0.762	0.918**	0.943**	0.957**	0.926**	1	
Grain yield	0.801**	0.798*	0.879**	0.893**	0.866*	-0.712	-0.722	0.914**	0.872**	0.671	0.751	1

* Correlation is significant at the 0.05 level.

** Correlation is significant at the 0.01 level.

NO_3-N- Nitrate N; NH_4-N- Ammonium N; HAN- Hydrolysable ammoniacal N; AAN- Amino acid N; ASN- Amino sugar N; UN- Unidentified hydrolysable N; NHN- Non hydrolysable N; VLC- Very labile C; LC- Labile C; LLC- Less labile C; NLC- Nom labile C

zero tillage), crop planting techniques (puddle-transplanting and direct seeding) and residue management (retention and removal) influence key soil carbon and nitrogen fractions alongside rice yield performance in an alluvial soil ecosystem. The results obtained have been discussed under this section.

Carbon dynamics in soil

The study revealed notable differences in soil carbon fractions under varying crop establishment methods, particularly in the very labile and labile carbon pools, which are considered sensitive indicators of short-term management changes. Treatments combining zero tillage with green gram residue incorporation specifically T4 and T8 consistently recorded the highest values of very labile and labile carbon, significantly outperforming conventional tillage-based treatments such as T1 and T5.

The enhanced labile C pools under CA-based systems can be attributed to minimal soil disturbance and residue incorporation from green gram which promoted the accumulation of easily mineralizable carbon forms (25). DSR and ZTW involve reduced soil disturbance and preserve soil aggregates from being exposed to the environmental agents like sunrays and air currents and as a result reduced oxidation of soil organic matter allow more labile carbon to accumulate. This aligns with findings of previous researchers (26), who reported a buildup of labile C under zero-till and residue-retained systems in Indo-Gangetic soils. Similarly, previous studies emphasized the importance of legume-based residue inputs in enhancing active C pools (27). A meta-analysis was reported a 21.4 % increase in soil organic carbon (SOC) in the 0–15cm layer under CA practices compared to conventional systems (28). Similarly, former studies showed that cover crops and legume residue inputs significantly increased microbial biomass carbon by 33 % and particulate organic carbon by 15 %, both of which closely correlate with the very labile and labile C fractions measured in this study (29). A recent long-term field study demonstrated similar trends, where CA treatments with mung bean integration and residue retention led to significant increases in coarse particulate organic matter (cPOM) and surface SOC, confirming that legume residue quality and placement are key to enhancing carbon fractions (30) . In contrast, the lowest labile carbon contents observed in T5 and T1 likely due to greater oxidation of organic matter triggered by frequent soil disturbances with heavy machineries, under conventional tillage, absence of residue addition and poor root biomass contribution. Such effects of intensive tillage on organic carbon depletion have been widely documented (31, 32).

Although the less labile and non-labile carbon fractions did not show statistically significant differences across treatments (as indicated by the non-significant CD values), a gradual increasing trend was observed under green gram-integrated and zero-till treatments. This suggests that even the more stable organic carbon pools respond positively to sustainable practices over time, though changes in these fractions are typically slower and require longer monitoring periods to become significant (33).

Nitrogen dynamics in soil

Inorganic N fractions

Irrespective of tillage intensity and planting techniques, the inclusion of green gram in the rotation resulted higher values of various N-fractions clearly establishing the beneficial role of legumes in enriching soil N-stocks. These results are in line with previous studies (34), where incorporation of green gram and Dhaincha residues significantly enhanced soil accessible N pools. Favorable C:N ratio of these legumes enables faster mineralization and subsequent enrichment of N-reserves (35). Notably, the content of NH_4^+–N was higher than NO_3^-–N across all treatments, which can be attributed to soil moisture regimes that limited nitrification, along with preferential retention of NH_4^- on soil exchange sites and slower nitrate formation. These trends are consistent with findings from similar agro-ecologies (36), where ammonium tends to dominate under reduced soil conditions and residue-retentive conservation agriculture systems.

Among the treatment combinations, treatments involving TPR reported higher NH_4^+–N content than their DSR counterparts whereas, DSR reported higher NO_3^-–N than their TPR counterparts. These results might be attributed to the aerobic conditions in Dry DSR, which promote fair gaseous exchange between soil and atmosphere and triggered activity of nitrifying bacteria, whereas the puddled conditions in TPR resulted in formation of anaerobic condition and led to ammonification (37). Meticulous insight of the data also revealed that both the inorganic N-fractions followed similar trend (T2>T1 ; T6>T5 ; T4>T3 ; T8>T7) which clearly emphasize the fact that Zero tillage practice implemented for wheat in the previous cycles enhanced the retention and utilization of both fractions. Reduced disturbance, coupled with residue-mediated improvements in soil organic matter and microbial activity, fostered sustained ammonification and nitrification processes (38). This integrated response aligns with recent findings (39, 40) and highlights the potential of conservation agriculture practices in optimizing soil inorganic nitrogen dynamics for improved crop nitrogen use efficiency.

Organic N-fractions

HAN was significantly higher in T4 followed closely by T8 and T3. Being the most labile N-fraction, HAN content has been closely related to the amount of organic residues added to the soil and magnitude of microbial decomposition of the added organic matter (41). Our findings can be attributed to combined effect of zero tillage, legume residue retention and dry DSR, which together created a biologically enriched and microbially active soil environment. Previous literatures strengthen our findings which reported that legume residues, being rich in nitrogen and low in C:N ratio, decompose rapidly and fuel microbial activity. Lesser mechanical interference of soil promotes macroaggregate formation and preserves microbial habitats, which ultimately resulted higher HAN (42). AAN, representing proteinaceous compounds, also followed similar trend. Treatments involving green gram residue outperformed their respective fallow counterparts. The higher values are likely due to increased root biomass, rhizodeposition and microbial biomass turnover induced by legume cultivation. As reported in previous studies (43), residues rich in labile carbon and nitrogen, such as those from pulses, accelerate microbial activity and protein transformation in the soil. ASN, primarily derived from microbial cell wall components such as glucosamine and muramic acid, serves as a stable indicator of microbial necro mass and long-term organic nitrogen stabilization (44). In conservation agriculture, minimal soil disturbance and improved aggregation physically protect the chemically resistant compounds like amino sugars. Theses physically protected and chemically stabilized mineral-associated organic matter promotes long term soil fertility (45), which supports our hypothesis well and good. Although UN and

NHN fractions did not differ significantly across treatments, numerically higher values were recorded in green gram-based ZT treatments (T4 and T8). These fractions represent more stabilized N pools and their gradual increase over time reflects the potential long-term benefits of conservation agriculture (CA) in enhancing soil organic N reserves. These findings are in agreement with those of former studies (46, 47). One more thing which is worth-mentioning is that the traditional practice, which is mostly followed by Indian farmers i.e., (T5: TPR-CTW-F) reported lowest numerical values in all the N-fractions, which raises a serious concern towards long term sustainability and also points out the need of shifting towards alternate crop establishment methods.

Crop yield

The significantly higher grain and straw yields observed under T8 and T7 can be directly linked to the enhanced levels of both soil carbon fractions and nitrogen pools observed under these systems. Treatments incorporating green gram residues and zero tillage probably led to an accumulation of labile and stable fractions such as amino sugar-N and Unidentified N, indicating a more biologically active and nutrient-rich soil environment. These organic pools are known to regulate nutrient supply through mineralization-immobilization turnover, ensuring better synchrony with crop nitrogen demand (48). The positive and significant correlation coefficients between grain yield and labile carbon fractions (e.g., r = 0.914 with VLC, r = 0.872 with LC) and nitrogen fractions (e.g., r = 0.893 with AAN, r = 0.879 with HAN) further substantiate this linkage, which aligns with the findings of (17). These correlations confirm that improved biological activity and nitrogen availability particularly under CA based treatments played a critical role in yield enhancement (49, 50). The synergistic effects of residue-induced C and N enrichment, combined with reduced soil disturbance under zero tillage, created favorable rhizosphere conditions that enhanced root proliferation, microbial activity and nutrient uptake, thereby translating into superior rice productivity (51). These findings align with earlier reports (52) and also noted that soil C and N fractions are strongly predictive of crop performance in conservation agriculture systems (26).

Conclusion

The present study demonstrates that conservation agriculture (CA)-based crop establishment methods, especially those involving zero tillage and legume residue (green gram) incorporation, significantly enhance soil organic carbon and nitrogen fractions and contribute to improved rice productivity. Treatments such as TPR-ZTW-GG and Dry DSR-ZTW-GG not only recorded higher concentrations of various C and N-fractions, but also achieved superior grain and straw yields. The positive correlations observed between labile C and N-fractions and crop yield affirm the pivotal role of biologically active C and N- pools in maintaining soil fertility and supporting plant growth. Additionally, the build-up of relatively stable fractions under CA practices indicates a gradual shift toward long-term nutrient stabilization and soil health improvement. Future studies should prioritize long-term and multi-location trials, integrate soil microbial and enzymatic activity assessments and evaluate nitrogen-use efficiency and greenhouse gas emissions to further validate and expand these findings.

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Authors' contributions

KK carried out the experiment, conducted laboratory analysis and prepared initial manuscript draft. SK conceived the idea of the experiment. SS proofread the initial manuscript draft and finetuned it. KB participated in data curation. MG examined the manuscript carefully and revised wherever needed. FH helped in statistical analysis of the data. AKS provided all the necessary support during conduction of the experiment. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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