

Functional groups and mineralization kinetics of soil organic matter under contrasting hydro-thermal regimes under conservation agriculture-based rice–wheat system in eastern Indo-Gangetic Plains

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Abstract

Soil organic carbon (SOC) sequestration is important to counteract anthropogenic climate change at the global level. Studying the effect of conservation agriculture (CA) on SOC dynamics in the presence of two distinctively different hydro-thermal regimes across the year in rice–wheat (RW) systems in eastern Indo-Gangetic Plains (E-IGP) is of topical interest. The stabilization mechanism of soil organic matter (SOM), and its effect on C mineralization kinetics in these conditions is not well understood. We collected soil samples from six combinations of CA and conventional farming in an ongoing experiment at CIMMYT-Borlaug Institute for South Asia, Bihar, India. CA enhanced SOC, specifically labile C, while decreasing mineral N, as a result of encapsulation/assimilation in aggregates/microbial biomass. Humic acids registered characteristic Fourier transform infrared (FTIR) peaks at 3200–3600 cm⁻¹, 2920–2930 cm⁻¹, 1645–1655 cm⁻¹ and 1220–1240 cm⁻¹, and displayed lesser degree of humification, aromaticity and redox status under CA. SOC and N mineralization were studied in two different hydro-thermal regimes pertaining to rice (submergence, 35°C; SM35) and wheat (field capacity, 25°C; FC25) growing periods of E-IGP. SM35 displayed temperature-mediated higher decay of SOC. Decay constants of C mineralization were lesser under CA compared with CT. CA promoted higher SOM stability, evidenced by lower decay rates of SOC and N, attributed to (1) better protection of SOM in well-aggregated soil structure and (2) an excess supply of fresh crop residues ensuring higher rate of SOM formation than its decay. Practising CA in E-IGP is imperative towards C-neutral agriculture, especially in the impending global warming scenario.

KEYWORDS

crop residue retention, decay constant, humic acid, labile carbon, mineral nitrogen, particulate organic matter, zero tillage

1 | INTRODUCTION

Soil C sequestration is of prime importance regarding offsetting the ill effects of global warming and greenhouse gas (GHG) emissions. Conservation agriculture (CA) is a crop production system involving minimum soil disturbance, soil cover through crop residues or other cover crops and diversified crop rotations, which is crucial for enhancing soil C sequestration (Dey et al., 2020). The rice (*Oryza sativa*)–wheat (*Triticum aestivum*) (RW) systems of Indian subtropics are often considered as the major sources of GHG emissions consisting of methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂) with global warming potential (GWP) of 88.5 Tg CO₂-C eq (Bhatia et al., 2012). The traditional RW system of Indo-Gangetic Plains (IGP) has a unique edaphic and climatic scenario. Rice is transplanted in puddled soils in hot *kharif* season and prefers continued submergence, whereas wheat is grown in well-drained dry soils having good tilth in cool *rabi* season. These annual conversions of soil from aerobic to anaerobic conditions and vice-versa cause several soil physical, chemical and biochemical changes that have a direct impact on the C and N cycling. The impact of CA on soil C under these highly dynamic edaphic conditions is of great topical interest and needs to be studied in detail. Furthermore, there are scarce studies on the dynamics of soil organic carbon (SOC) in a calcareous soil, which needs to be researched in detail.

The intensive cultivation of RW in a system mode for more than five decades led to a decline in soil organic matter (SOM), in terms of quality and quantity which threatens the sustainability of the system. Several studies reported positive effects of CA on labile C pools, that is dichromate oxidisable C (Chan et al., 2001; Dey et al., 2020), microbial biomass C (Spedding et al., 2004) and particulate matter associated SOC (POM-C) (Cambardella & Elliott, 1992; Six et al., 2000). Decay rates of soil C mineralization were reported to be lower under CA compared with conventional practices (Jat et al., 2019; Parihar et al., 2019). There are abundant reports of increased soil N concentration consequent to CA adoption (Dey et al., 2016; Dikgwatlhe et al., 2014), with a concomitant increase in aggregate associated N and SOC (Bhattacharyya et al., 2019). Therefore, majority of previous studies dealt with different pools of C, which can be measured via chemical oxidation or mechanical separation. On the contrary, there are not many instances, where researchers studied the chemical configuration or functional groups associated with soil organic matter. The changes in bio-chemical makeup of SOM can be assessed through studying the configuration of functional groups of humic acids (HA), which undergoes a sea change, in response to the tillage and crop residue management practices (Datta et al., 2022; González-Pérez

et al., 2007). Studying the bio-chemical recalcitrance of SOM contributing towards SOC sequestration under CA would be interesting under subtropical RW systems. In the present study, we used the Fourier transform infrared (FTIR) spectra of HA as a tool for measurement of humification, aromaticity, recalcitrance and redox status of the HA. The C in soil can be stabilized through physical protection within soil aggregates or through chemical recalcitrance through formation of complex organic molecules (Lal, 2013). Both the stabilization mechanisms work in tandem, but the nature of prevalent stabilization mechanism plays an important part on the fate of soil-sequestered C. In the current study, we attempted to assess the nature of C stabilization mechanism through studying particulate organic matter (POM) and HA in soil.

An equilibrium between mineralization and immobilization is important with respect to C sequestration, soil respiration and supply of plant available N. The alterations in tillage and residue management under CA prominently affect C and N mineralization (Jat et al., 2019; Parihar et al., 2019). Temperature and moisture regimes affect SOC and N mineralization by controlling bio-chemical reaction kinetics, microbial activity and biomass responsible for the process (Spedding et al., 2004). An enhancement in temperature or moisture regime within certain provisional ranges generally enhances SOM mineralization. The dependence of SOM mineralization on hydro-thermal regimes should play a very effective role in enhancement of SOM through CA adoption in the ever-changing hydro-thermal scenario in RW system and needs to be studied. Earlier studies established the potential of rice-rice system to conserve organic carbon in subtropical climate (Mandal et al., 2007). In the present study, we attempted to assess the temporal variations in mineralization pattern of SOM in RW system through different cropping seasons. Furthermore, nature of C stabilization is expected to play an important role in C mineralization kinetics (Lal, 2013). In the present study, we tried to assess the effect of different C stabilization mechanisms under CA with the mineralization pattern of SOM.

In the present study, the effectiveness of CA practices in altering SOC and N mineralization in two different hydro-thermal regimes (present during the rainy and winter seasons) was assessed. The paper also deals with a detailed study on the effect of tillage and residue management on different pools of SOC and N, and different functional groups of HA. The hypotheses of this study were as follows: (i) adoption of CA enhances the quantity of SOC and N, along with the quality of SOM, and (ii) mineralization of SOC and N would occur slowly under CA practices, and will vary under different hydro-thermal regimes. To address these hypotheses, the objectives were as follows: (i) to evaluate the effects of different CA practices on different SOC and N pools, and bio-chemical characteristics

of soil HA, and (ii) to study SOC and N mineralization as affected by continuous CA practices under different hydro-thermal regimes pertaining to monsoon rice and winter wheat growing conditions of the Eastern IGP.

2 | MATERIALS AND METHODS

2.1 | Study site characteristics

This study was carried out at the experimental farm of CIMMYT-Borlaug Institute for South Asia, Samastipur, Bihar, India (25° 59' N latitude, 85° 41' E longitude, altitude of 53.0 m asl), representing eastern IGP possessing a subtropical hot and humid climate with three distinct seasons, *that is* summer (March–first fortnight of June), rainy (second fortnight of June–September) and winter (October–February). The average annual rainfall is 1300 mm, out of which ~80% occurs in the rainy season. The mean monthly maximum and minimum temperatures range between ~24 to 37°C and ~9 to 27°C, respectively. The soil is calcareous and falls under great group Calciorthent (Dey et al., 2020). The initial soil characteristics (0–15 cm) of the experimental site are presented in Table 1.

2.2 | Treatments, experimental design and crop management

The long-term CA experiment was established during monsoon 2006 involving different combinations of tillage, crop establishment and residue management practices in

TABLE 1 Initial soil properties (monsoon 2006) of the study site at CIMMYT-BISA, Samastipur, India.

Soil properties (0–15 cm depth)	Value/ Category
Soil texture	Clay loam
pH (1:2)	8.6
^a Free CaCO ₃ (%)	34
Walkley-Black soil organic carbon (g kg ⁻¹)	6.8
Alkaline KMnO ₄ oxidisable N (mg kg ⁻¹)	112
0.5 M NaHCO ₃ (pH 8.5) extractable P (mg kg ⁻¹)	14.0
Neutral normal NH ₄ OAc extractable K (mg kg ⁻¹)	60.5
^a Bulk density (Mg m ⁻³)	1.34
^a Total soil organic carbon concentration (g kg ⁻¹)	26.7
^a Total soil inorganic carbon concentration (g kg ⁻¹)	40.8
^a Total soil organic carbon stock (Mg ha ⁻¹)	53.7
^a Total soil inorganic carbon stock (Mg ha ⁻¹)	82.0

^aBased on the analysis of uncultivated soil (since inception of the experiment) drawn from adjoining area of the experimental field.

a rice–wheat rotation (Table 2) (Jat et al., 2014). All treatments were completely randomized and replicated thrice within a block. The individual plot area was 1400 m² (70 m × 20 m). Rice cultivar ‘PHB 71’ and wheat cultivar ‘PBW 343’ were used for the first 2 years (2006–07), and thereafter, these were replaced by ‘RajendraMashuri’ and ‘HD 2733’, respectively.

Both rice and wheat crops were fertilized with 150, 26 and 33 kg of N, P and K per hectare, respectively, irrespective of the treatments. Eleven per cent of N and the total amount of P and K were applied through di-ammonium phosphate (DAP) and muriate of potash (MOP), respectively, at sowing with a seed-cum-fertilizer drill, and the remaining N was broadcasted in two equal splits as urea at tillering and panicle initiation of crop. In rice, ZnSO₄ was applied @25 kg ha⁻¹ (in alternate years). A detailed description of crop management in different treatments in this experiment is given by Jat et al. (2014).

2.3 | Collection and processing of soil samples

After the conclusion of six cropping cycles (after harvest of wheat), two sets of samples were collected from the surface (0–15 cm) soil layer. Samples of the first set were air-dried, ground in a wooden mortar and pestle, and sieved through a 2 mm sieve. For C analysis, a set of sub-samples was further sieved through a 0.2 mm sieve. Humic acids were extracted from the same 2 mm sieved samples. From the second set of undisturbed soil samples, a set of sub-samples was taken for determination of microbial biomass C and N, and mineral N. Another set of sub-samples was used for extraction of POM. Rest of the undisturbed moist soil samples were used for studying mineralization behaviour of SOC and N. Samples were transported in ice boxes and stored in a refrigerator at 4°C.

2.4 | Analysis of carbon and nitrogen in soil

Total soil C and N of bulk soil samples (passed through a 0.2 mm sieve) were determined through CHN analyser (EuroVector Instruments, EA 3000, Italy). Total SOC was computed through subtracting total SIC (Dey et al., 2020) from the total C. Very labile SOC (SOC_{VL}), labile SOC (SOC_L), less labile SOC (SOC_{LL}) and non-labile SOC (SOC_{NL}) were estimated following the modified Walkley–Black method (Chan et al., 2001), and lability was calculated as:

$$\text{Lability of SOC} = \frac{\text{Very labile SOC} + \text{Labile SOC} + \text{Less labile SOC}}{\text{Non-labile SOC}}$$

TABLE 2 Abbreviations and description of tillage, crop establishment and residue management protocols under different treatments.

S. No.	Treatment	Details of operations performed
1	CT-CT; Conventional-till rice followed by conventional-till wheat.	In rice, three harrowing was done under aerobic conditions followed by two passes of cultivator under ponded water. Twenty-five-day-old rice seedlings were then manually transplanted in a random geometry with 30 seedlings m ⁻² . After rice, wheat was sowed via broadcasting of 150 kg seeds ha ⁻¹ following conventional tillage (two passes of harrow, one pass of cultivator followed by one planking). All cereal residues were removed.
2	CT-ZT; Conventional-till rice followed by zero-till wheat.	After rice, wheat was directly drilled into flat soil under zero-till conditions using zero-till seed-cum-fertilizer drill with seed rate of 100 kg seeds ha ⁻¹ . The seeding depth was kept 3–4 cm and a row spacing of 20 cm was maintained. All cereal residues were removed.
3	ZT-CT; zero-till direct seeded rice followed by conventional-till wheat.	In rice crop, seeds were directly drilled at 20 cm row spacing using zero-till seed-cum-fertilizer drill at a seed rate of 25 kg ha ⁻¹ . The seeding depth was maintained at 2–3 cm. wheat was sown via broadcasting following conventional tillage. All cereal residues were removed.
4	ZT-ZT; zero-till direct seeded rice followed by zero-till wheat.	Both rice and wheat were sown under zero tillage conditions via direct drilling using zero-till seed-cum-fertilizer drill. All residues were removed.
5	ZT-ZT + R; zero-till direct seeded rice followed by zero-till wheat. Residue retention for both crops.	Both rice and wheat were sown under zero tillage conditions via direct drilling using zero-till seed-cum-fertilizer planter. Fifty per cent of the rice residue was retained during wheat and twenty per cent wheat residues retained during rice crop.
6	PB-PB + R; Direct seeded rice in permanent raised bed followed by wheat on permanent raised beds. Residue retention for both crops.	In rice crop, two rows (30 cm apart) of seeds were directly drilled (20 kg seed ha ⁻¹) on each raised beds (10–12 cm height) having 37 cm top of the bed and 67 cm furrow to furrow spacing using a multi-crop raised bed planter. In wheat crop, two rows of wheat (30 cm apart) were established on each permanent raised bed at seed rate of 75 kg seed ha ⁻¹ . During wheat, the raised beds were reshaped using reshaping shovel of the raised bed planter in one-go, that is seeding and reshaping operations together. Fifty per cent of the rice residue was retained during wheat and twenty per cent wheat residues retained during rice.

The values of different SOC pools of the reference sample from nearby uncultivated areas are given in Table 1. Carbon management index (CMI) was calculated using the following equations.

$$\text{Carbon Pool Index (CPI)} \\ = \text{Sample total SOC} / \text{Reference total SOC}$$

$$\text{Lability Index of C (LI)} = \text{Lability of SOC in sample soil} \\ / \text{Lability of SOC in reference soil}$$

$$\text{Carbon management index (CMI)} = \text{CPI} \times \text{LI} \times 100$$

The POM was extracted from the 8-mm sieved soil, through shaking with 0.5% Na hexametaphosphate followed by sieving through a 0.053 mm sieve (Cambardella & Elliott, 1992). Particulate organic matter associated with C and N (POM-C and POM-N) was then determined through the CHN analyser. Soil microbial biomass C (SMB-C) and N (SMB-N) were determined in fresh undisturbed moist soil samples through fumigation extraction (Jenkinson & Ladd, 1981), through assumption of extraction coefficients as 0.35 and 0.45, respectively. Mineral N was extracted with 2M KCl in moist undisturbed soil samples and estimated

following steam distillation with Devardas' alloy and MgO (Rowell, 1994).

The SOC was estimated on the basis of equivalent soil mass (ESM) (Wendt & Hauser, 2013) through the formula stated below for better and realistic representation in the experimental treatments which differed in tillage and crop residue management.

$$M_{\text{soil (DL)}} = \frac{M_{\text{sample (DL)}}}{A_{\text{sample (DL)}}} \times 100$$

where $M_{\text{soil (DL)}}$ (Mg ha⁻¹) is soil mass of a sample depth layer (DL) per unit area. $M_{\text{sample (DL)}}$ (g) is the dry soil mass of the core sample taken from the representative DL. $A_{\text{sample (DL)}}$ (cm²) is the cross-sectional area of the core sampler.

$$M_{\text{SOC (DL)}} = \frac{M_{\text{soil (DL)}} \times C_{\text{SOC(DL)}}}{1000}$$

where $M_{\text{SOC(DL)}}$ (Mg ha⁻¹) is SOC on ESM basis of the sample DL. $C_{\text{SOC(DL)}}$ is the concentration of SOC (g kg⁻¹).

$$M_{\text{N (DL)}} = \frac{M_{\text{soil (DL)}} \times C_{\text{N(DL)}}}{1000}$$

where $M_{N(DL)}$ (Mg ha^{-1}) is soil N on ESM basis of the sample DL. $C_{N(DL)}$ is the concentration of soil N (g kg^{-1}).

2.5 | Alkali extraction of soil organic matter and its characterization

Repeated alkali extraction using 0.5N NaOH + 0.1N $\text{Na}_4\text{P}_2\text{O}_7$ (till the obtainment of a light-coloured extract) in soils pre-refluxed with benzene was followed under a non-reactive N_2 atmosphere for extraction of humic and fulvic acids (Swift et al., 1996). The extracts were then acidified with HCl to pH 1–2 for the precipitation of HAs. The HA precipitates were treated with HCl-HF mixture repeatedly to reduce the ash content below 1%. The ash-free HA was then dialysed through snake-skin dialysis tubing (10kDa) under continuous distilled water flow. The HA were then lyophilized and stored. The HA were analysed for functional groups through FTIR spectrophotometer (Perkin Elmer, 1600) over the range of 4000 to 400 cm^{-1} , at 16 nm s^{-1} . Ratios of different peak heights were used to characterize HA. Humification index was calculated as the ratio of peak heights at $1655\text{--}1630\text{ cm}^{-1}$ and $3600\text{--}3200\text{ cm}^{-1}$. Ratio of peak heights at $1655\text{--}1630\text{ cm}^{-1}$ and $2930\text{--}2920\text{ cm}^{-1}$ indicated aromaticity index. Lastly, the ratios of peak heights at $1220\text{--}1240\text{ cm}^{-1}$ and either of $3200\text{--}3600\text{ cm}^{-1}$ and $2920\text{--}2930\text{ cm}^{-1}$ were termed as redox status or polarity index (Amir et al., 2004).

2.6 | Monitoring soil organic carbon and nitrogen mineralization

An incubation study was undertaken under two hydro-thermal conditions; (i) continuous submergence (maintenance of 2.5 cm standing water) at 35°C temperature (SM35) simulating monsoon rice growing conditions, and (ii) field capacity moisture regime at 25°C temperature (FC35) simulating winter wheat growing conditions at eastern IGP. Cumulative C and N mineralization (C_t and N_t) were studied at 0-, 1-, 2-, 4-, 8-, 16-, 32- and 64-day intervals.

The alkali trap method (using 0.5N and 1N NaOH up to 16 days, and after 16 days, respectively) following back titration with HCl was used to measure CO_2 evolution at each interval (Anderson, 1982). Mineral N was measured using steam distillation (Rowell, 1994).

A first-order two-component exponential model developed by Andr en and Paustian (1987) was applied to the mineralization data to determine the kinetics.

$$C_t = C_1(1 - e^{-Kc1t}) + C_2(1 - e^{-Kc2t}) \text{ and} \\ N_t = N_1(1 - e^{-Kn1t}) + N_2(1 - e^{-Kn2t})$$

where C_1 ($\text{mg } 100\text{ g}^{-1}$ soil) and N_1 ($\text{mg } 100\text{ g}^{-1}$ soil) are the amounts of labile SOC and potentially mineralizable N, respectively. The C_2 ($\text{mg } 100\text{ g}^{-1}$ soil) and N_2 ($\text{mg } 100\text{ g}^{-1}$ soil) are the amounts of recalcitrant SOC and potentially non-mineralizable N, respectively. The C_t ($\text{mg } 100\text{ g}^{-1}$ soil) and N_t ($\text{mg } 100\text{ g}^{-1}$ soil) are the pools of SOC and N mineralized at time t (days). The $Kc1$ ($\text{mg } 100\text{ g}^{-1}$ soil day^{-1}) and $Kn1$ ($\text{mg } 100\text{ g}^{-1}$ soil day^{-1}) are the decay rate constants for the labile pool of SOC and N, respectively. The $Kc2$ ($\text{mg } 100\text{ g}^{-1}$ soil day^{-1}) and $Kn2$ ($\text{mg } 100\text{ g}^{-1}$ soil day^{-1}) are the decay rate coefficients for the recalcitrant pool of SOC and N, respectively.

2.7 | Carbon input calculation

Grain and straw yields were recorded annually. Rhizodeposition of rice and wheat crops was assumed as ~15.0% and 12.6% of the total aboveground biomass, respectively (Bronson et al., 1998). Root: shoot ratios were calculated, and root biomass was derived as 17.7% and 13.5% of the total aboveground biomass of rice and wheat crops, respectively. Stubble biomass left in the field was estimated as 10% and 4% of the straw biomass of rice and wheat, respectively. The C content in stubble and root was assumed as ~33.5% and 35.0% for rice, and 41.9% and 39.3% for wheat, respectively (Mandal et al., 2007). The C content in rhizodeposition was assumed as 74% (Benbi & Brar, 2009). The crop residue of rice and wheat crops contains ~52.6% and 48.2% C, respectively (Das et al., 2013). The cumulative C inputs to the soil were estimated as summation of C inputs through crop stubbles, roots, rhizodepositions and crop residue retentions as per treatments (Table 2).

2.8 | Statistical analysis

Analysis of variance (ANOVA) for completely randomized block design was performed using the Statistical Analysis System (SAS version 9.2) Software. The replicated mineralization data were fitted to a first-order two-component exponential model using Solver function of Microsoft Excel (Microsoft Office, version 2016).

3 | RESULTS

3.1 | Soil organic carbon and its different forms

Treatments ZT-CT, ZT-ZT, ZT-ZT+R and PB-PB+R had nearly 13, 12, 20 and 11%, respectively, more concentrations of total SOC than CTR-CTW (Table 3). The

TABLE 3 Effect of continuous CA practices (6 years) on SOC and N, and its distribution in different pools.

Treatment	Total SOC (g kg ⁻¹)	SOC _{VL} (g kg ⁻¹)	SOC _L (g kg ⁻¹)	SOC _{LL} (g kg ⁻¹)	SOC _{NL} (g kg ⁻¹)	POM-C (g kg ⁻¹)	MBC (mg kg ⁻¹)	TSN (g kg ⁻¹)	POM-N (g kg ⁻¹)	MBN (mg kg ⁻¹)	Mineral N (mg kg ⁻¹)
CT-CT	22.9d	2.55c	1.05c	0.76c	18.5a	3.17c	203c	1.20c	0.19d	26.5b	35.3b
CT-ZT	23.9cd	2.35c	1.09c	1.21a	19.3a	3.59bc	206c	1.18c	0.23c	22.1b	26.2d
ZT-CT	25.9b	2.99b	2.01b	0.82bc	20.1a	3.75ab	212bc	1.38abc	0.28b	22.8b	15.4e
ZT-ZT	25.7b	3.50a	2.26ab	1.10ab	18.8a	4.09ab	222bc	1.29bc	0.20cd	24.8b	26.3d
ZT-ZT + R	27.5a	3.84a	2.52a	1.30a	19.9a	4.26a	294a	1.51ab	0.33a	34.3a	28.2c
PB-PB + R	25.4bc	2.61bc	1.84b	1.00abc	20.0a	3.94ab	258ab	1.53a	0.21cd	37.0a	36.9a
Mean	25.2	2.97	1.80	1.03	19.4	3.80	232	1.39	0.23	27.9	24.1

Note: Values within a column followed by the same letter are not significantly different at $p \leq .05$.

Abbreviations: CT-CT, transplanted rice followed by conventional-till wheat; CT-ZT, CT rice followed by zero-till wheat; MBC, Microbial biomass carbon; PB-PB + R, R-W system on permanent beds with crop residue retention for both crops; POM-C, particulate organic matter associated carbon; ZT-CT, ZT direct seeded rice followed by CT wheat; ZT-ZT, ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with crop residue retention of both crops; SOC, soil organic carbon; SOC_L, labile SOC; SOC_{LL}, less labile SOC; SOC_{NL}, non-labile SOC; SOC_{VL}, very labile SOC; WBC, Walkley-Black carbon.

ZT-ZT + R had significantly ($p < .05$) higher concentration of total SOC than ZT-ZT and PB-PB + R. On the contrary, the SOC stock (on ESM basis) was similar under treatments ZT-CT, ZT-ZT and ZT-ZT + R (Figure 1). The treatment PB-PB + R had significantly lower SOC stock (on ESM basis) compared with that under ZT-ZT + R. Averaged across treatments, SOC_{NL}, SOC_{LL}, SOC_L and SOC_{VL} contributed 77, 4, 7 and 12% of total SOC, respectively (Table 3). Under ZT-ZT, SOC_{VL} concentrations were 37% higher compared with CT-CT. The ZT-ZT + R registered an additional ~10% increase in SOC_{VL} over ZT-ZT. PB-PB + R had significantly lower SOC_{VL} compared with ZT-ZT and ZT-ZT + R. All ZT- rice and PB- rice treatments had significantly higher SOC_L (1.84 to 2.52 g kg⁻¹) compared with CT-CT (1.05 g kg⁻¹). PB-PB + R had 19 and 27% lesser SOC_L than ZT-ZT and ZT-ZT + R plots, respectively (Table 3). The SOC_{LL} concentration was significantly higher under ZT-ZT (1.10 g kg⁻¹) and ZT-ZT + R (1.30 g kg⁻¹) compared with CT-CT (0.76 g kg⁻¹). Different tillage, crop establishment and residue management practices did not significantly affect SOC_{NL} concentrations.

Compared with CT-CT, POM-C was 18, 29, 34 and 24% higher under ZT-CT, ZT-ZT, ZT-ZT + R and PB-PB + R plots, respectively (Table 3). All ZT-rice treatments had similar amounts of POM-C, suggesting no beneficial effect of residue retention. ZT-ZT + R and PB-PB + R had significantly higher MBC compared with CT-CT, respectively, whereas ZT-rice plots without residue did not show beneficial effects on MBC, over CT-CT, suggesting a beneficial effect of residue retention.

3.2 | Soil nitrogen and its different forms

The total soil N was 26 and 28% higher under ZT-ZT + R and PB-PB + R, respectively, compared with CT-CT (Table 3). The treatments ZT-CT, ZT-ZT, ZT-ZT + R and PB-PB + R registered similar values of total soil N stock (on ESM basis). These treatments registered ~15%–26% higher values of soil N stock compared with CT-CT or CT-ZT (Figure 1). The ZT-ZT + R had the highest POM-N (0.33 g kg⁻¹), significantly greater than all other treatments (Table 3). Alike MBC, MBN was not affected by alteration of tillage practices. ZT-ZT + R and PB-PB + R plots registered 29 and 40% higher MBN, respectively, compared with CT-CT (Table 3). The CA practices decreased mineral N over the conventional practice (Table 3). ZT-CT, ZT-ZT and ZT-ZT + R had 56, 25 and 20% less mineral N, respectively, than CT-CT (Table 3). Despite treatments ZT-ZT + R and PB-PB + R registering similar total N, the former had higher POM-N compared with the latter.

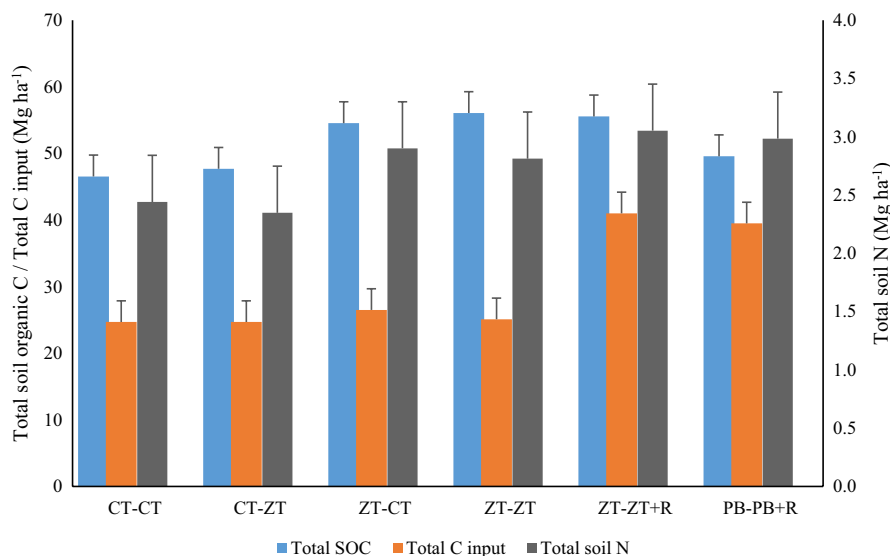


FIGURE 1 Estimate of total C inputs to soil under different treatments (Mg ha^{-1}), and status of total soil organic carbon (SOC) and N stocks (Mg ha^{-1}) on equivalent soil mass basis. CT-CT: transplanted rice followed by conventional-till wheat; CT-ZT: CT rice followed by zero-till wheat; ZT-CT: ZT direct seeded rice followed by CT wheat; ZT-ZT: ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with crop residue retention of both crops; PB-PB + R, R-W system on permanent beds with crop residue retention for both crops. Error bars represent LSD ($p < .05$).

3.3 | Humic acid

The HA from all the plots registered characteristic FTIR peaks at $3200\text{--}3600\text{ cm}^{-1}$, $2920\text{--}2930\text{ cm}^{-1}$, $1645\text{--}1655\text{ cm}^{-1}$ and $1220\text{--}1240\text{ cm}^{-1}$ (Figure 2). These main recorded bands on the FTIR spectral absorption plots were assigned to different functional groups (González-Pérez et al., 2007). The broad bands at $3600\text{--}3200\text{ cm}^{-1}$ possibly owed to the stretching vibration of hydrogen-bonded hydroxyl (OH) groups of alcohols, phenols and organic acids. The peak at $2930\text{--}2920\text{ cm}^{-1}$ was because of the stretching vibration of C-H of alkyl groups. The broad bands at $1655\text{--}1630\text{ cm}^{-1}$ corresponded to aromatic C=C and C=O bonds in amides, conjugated ketones and quinones. Lastly, the weak bands at $1240\text{--}1220\text{ cm}^{-1}$ corresponded to C-O stretching of aliphatic ketone and O-H bending of carboxyl groups. The humification index indicated the proportion between C=O and O-H systems, implying condensation and humification. Treatments ZT-ZT + R and PB-PB + R registered lower values of the humification index compared with CT-CT (Table 4). On the contrary, the aromaticity index indicated the proportion between aromatic and aliphatic systems. The CT rice treatments registered the highest value of aromaticity index, and the treatment ZT-CT registered the lowest value. The polarity indices indicated either the proportion between aliphatic C=O, COO- and O-H systems, or the proportion between aliphatic C=O, COO- and alkyl C-H systems. In other words, polarity indices described relative contents of high-polarity groups to that of low-polarity groups. The

values of polarity indices were lowest under ZT-ZT + R, implying low redox status of HAs under CA (Table 4).

3.4 | Soil organic carbon mineralization

On Day 4, maximum cumulative SOC mineralization (Ct) was noticed under ZT-ZT + R, followed by ZT-ZT and ZT-CT under SM35 (Figure 3). The Ct was significantly higher under CA treatments than CT-CT. The ZT-ZT + R had 29% higher Ct than ZT-ZT. On the contrary, residue retention in permanent beds resulted in ~31% lower Ct compared with ZT-ZT. On Days 16, 32 and 64, similar Ct was registered under ZT-ZT and ZT-ZT + R that were significantly higher than CT-CT (Figure 3). The Ct under PB-PB + R was significantly lower compared with ZT-ZT and ZT-ZT + R.

Higher Ct was observed under ZT-ZT and ZT-ZT + R than CT-CT on Days 4, 8 and 16, with the values being ~10%–18% higher under the CA treatments in FC25 (Figure 3). On Days 32 and 64, following the same trend, ZT-ZT and ZT-ZT + R had 28%–38% higher Ct than CT-CT. The PB-PB + R registered 16%–33% lower Ct compared with ZT-ZT and ZT-ZT + R on these days.

3.5 | Soil nitrogen mineralization

There were no detectable changes in cumulative N mineralization (Nt) fluxes with time up to the 16th day of incubation, irrespective of treatments under SM35. On Days 32 and 64, soils under ZT-ZT + R had the highest values of Nt

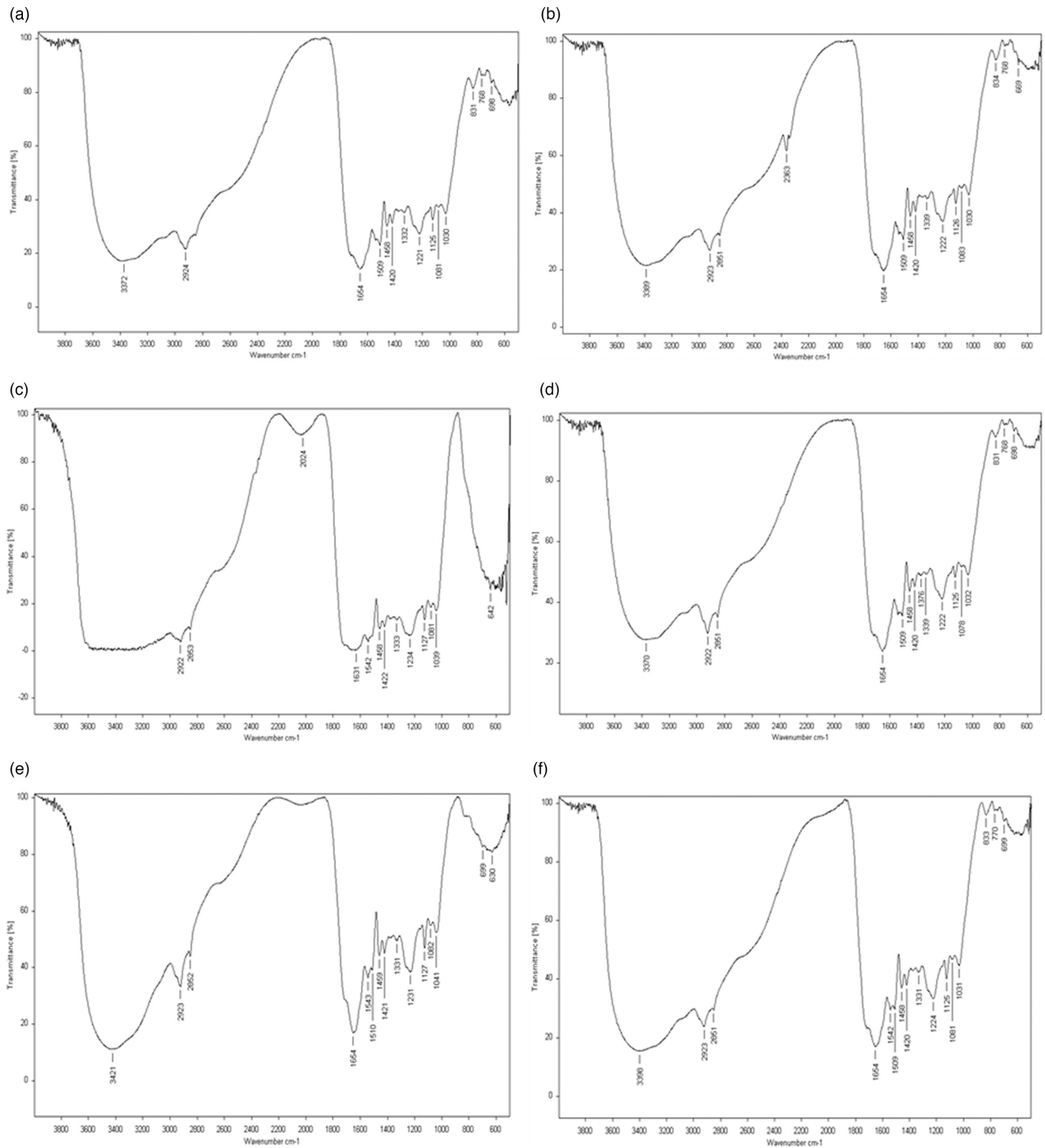


FIGURE 2 Fourier transform infrared (FTIR) spectra of humic acid extracted from (a) CT-CT, (b) CT-ZT, (c) ZT-CT, (d) ZT-ZT, (e) ZT-ZT+R and (f) PB-PB+R. CT-CT: Transplanted rice followed by conventional-tilt wheat; CT-ZT: CT rice followed by zero-tilt wheat; ZT-CT: ZT direct seeded rice followed by CT wheat; ZT-ZT: ZT direct seeded rice followed by ZT wheat; ZT-ZT+R, ZT direct seeded rice followed by ZT wheat with residue retention of both crops; PB-PB+R, R-W system on permanent beds with residue retention for both crops.

(12.2 and 25.6 mg N 100 g⁻¹ soil, respectively) (Figure 4). On Day 64, ZT-ZT had significantly higher Nt compared with CT-CT and PB-PB+R.

Under FC25, there was no detectable change in Nt with time up to Day 8 (Figure 4). On Day 16, ZT-ZT+R

registered significantly higher Nt compared with CT-CT, ZT-ZT and PB-PB+R (Figure 4). On Days 32 and 64, ZT-ZT+R registered ~15 and 23% higher Nt, respectively, compared with CT-CT. Treatments PB-PB+R, ZT-ZT and CT-CT had similar mineral N in these intervals (Figure 4).

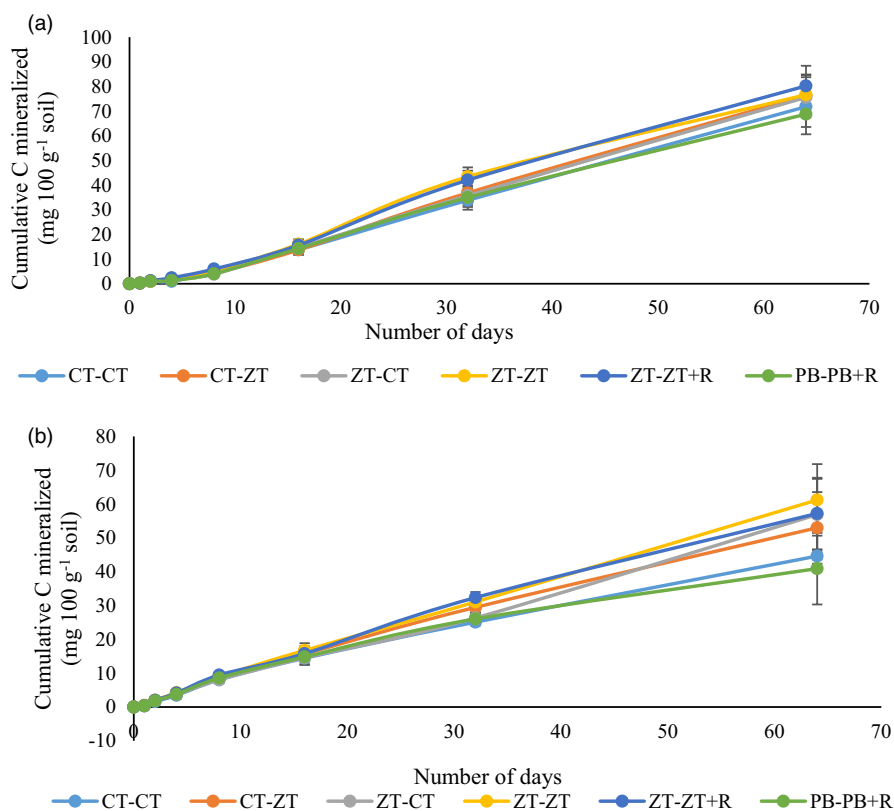
TABLE 4 Structural indices of humic acids as derived from semi-quantitative FTIR analysis.

Treatment	Ratio of peak lengths (Intensity of IR absorption)			
	Humification/ Condensation	Aromaticity	Redox status/Polarity	
	(1645–1655 cm ⁻¹)/ (3200–3600 cm ⁻¹)	(1645–1655 cm ⁻¹)/ (2920–2930 cm ⁻¹)	(1220–1240 cm ⁻¹)/ (3200–3600 cm ⁻¹)	(1220–1240 cm ⁻¹)/ (2920–2930 cm ⁻¹)
CT-CT	1.04a	1.09a	0.89ab	0.94a
CT-ZT	1.02ab	1.09a	0.81ab	0.87ab
ZT-CT	1.02ab	1.04c	0.95a	0.98a
ZT-ZT	1.04a	1.07ab	0.81ab	0.84ab
ZT-ZT + R	0.93c	1.06bc	0.64c	0.74b
PB-PB + R	0.97bc	1.07ab	0.78bc	0.87ab
Mean	1.00	1.07	0.79	0.86

Note: Values within a column followed by the same letter are not significantly different at $p \leq .05$.

Abbreviations: CT-CT, transplanted rice followed by conventional-till wheat; CT-ZT, CT rice followed by zero-till wheat; FTIR, Fourier transform infrared spectroscopy; PB-PB + R, R-W system on permanent beds with crop residue retention for both crops; ZT-CT, ZT direct seeded rice followed by CT wheat; ZT-ZT, ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with crop residue retention of both crops.

FIGURE 3 Cumulative soil organic C mineralized at (a) 35°C under continuous submergence and (b) 25°C under field capacity. CT-CT: Transplanted rice followed by conventional-till wheat; CT-ZT: CT rice followed by zero-till wheat; ZT-CT: ZT direct seeded rice followed by CT wheat; ZT-ZT: ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with residue retention of both crops; PB-PB + R, R-W system on permanent beds with residue retention for both crops. Error bars represent LSD ($p < .05$).



4 | DISCUSSION

4.1 | Effect of conservation agriculture on different forms of soil organic carbon

The estimated C input over the experimental period under ZT-ZT+R and PB-PB+R was 41 and 39.5 Mg ha⁻¹ (Figure 1), whereas the values ranged

from 24.7 to 25.1 Mg ha⁻¹ in the rest of the treatments. Substantial amount of C input under ZT-ZT + R helped in total SOC build-up. The calcareousness of the study site in combination with its high clay percentage added uniqueness to the study and resulted in some interesting findings. Majority of the SOC was present in non-labile form, whereas labile SOC contributed only ~25% to it (Table 3). Reduced intensity of tillage

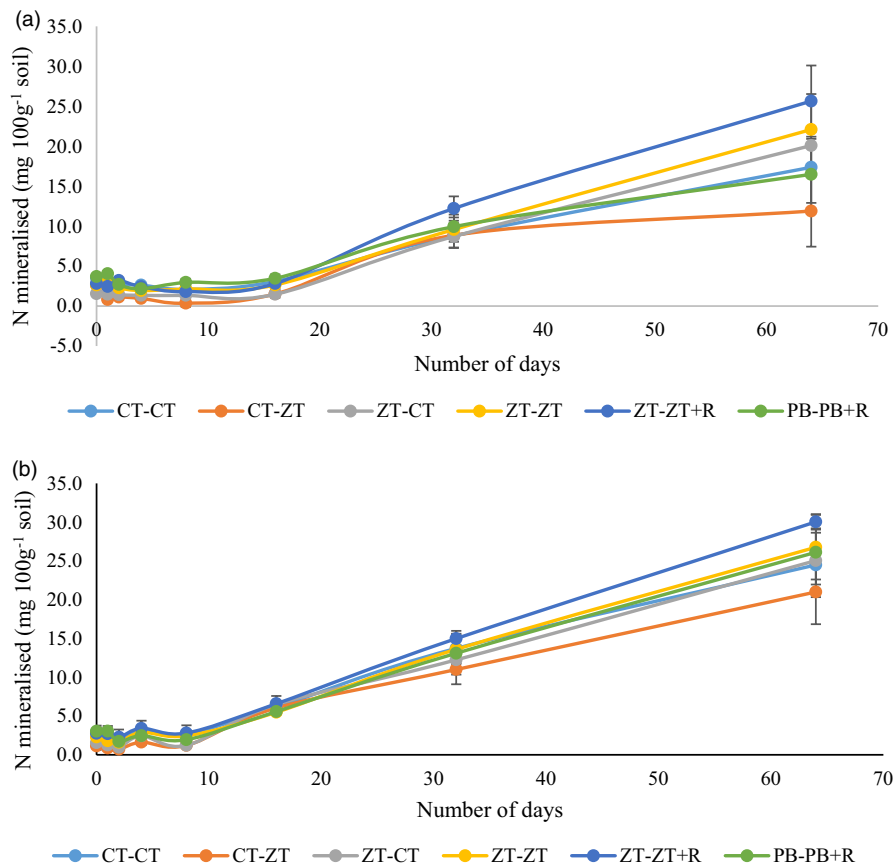


FIGURE 4 Cumulative soil N mineralized at (a) 35°C under continuous submergence and (b) 25°C under field capacity. CT-CT: Transplanted rice followed by conventional-till wheat; CT-ZT: CT rice followed by zero-till wheat; ZT-CT: ZT direct seeded rice followed by CT wheat; ZT-ZT: ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with residue retention of both crops; PB-PB + R, R-W system on permanent beds with residue retention for both crops. Error bars represent LSD ($p < .05$).

operations under double ZT treatments promoted less disruption of soil aggregates and consequently greater physical protection of SOC inside macroaggregates (Six et al., 2000). The POM represents organic matter associated with aggregates $>0.53 \mu$ diameter (Cambardella & Elliott, 1992). Slow macroaggregate turnover under ZT-ZT + R allowed time for the formation of POM from recent crop-derived organic matter and subsequent encapsulation of this POM by mineral particles and microbial by-products to form stable aggregates containing young crop-derived C (Table 3) (Bhattacharyya et al., 2019; Six et al., 2000). In contrast, the turnover of macroaggregates in CT is faster, providing less opportunity for formation of POM and stable aggregates (Six et al., 2000). The significant positive correlations of different SOC pools, that is Walkley-Black C, SOC_{VL} and SOC_L with POM-C (with r -values ranging from 0.46 to 0.59) ascertain the importance of physical protection towards enhancement of SOC. Surface retained residues provided protection against raindrop impact, besides providing a steady source of C. Despite similar amount of residue input under ZT-ZT + R and PB-PB + R, periodical reshaping of beds resulted in loss of SOC under the latter case (Figure 1 and Table 3). Additionally, the exposed surface areas under PB-PB + R are generally higher compared with those under flat beds (Dey et al., 2020; Jat et al., 2019; Parihar et al., 2019),

promoting SOM decomposition, and a loss of labile fractions of SOC. Continuous supply of fresh C input under ZT-ZT + R resulted in ~64% higher values of C lability and LI, compared with CT-CT (Figure 5). The treatment ZT-ZT also registered significantly higher values of C lability and LI compared with CT-CT. The enhancement in C lability under ZT-ZT and ZT-ZT + R in the current experimental soil, where majority of SOC resides in non-labile pool, is a definite indication towards the improvement in quality of SOC. Despite having similar C input, PB-PB + R reported significantly lesser values of C lability and LI, compared with ZT-ZT + R pertaining to loss of labile C. The dominance of physical protection over chemical stabilization of SOC under ZT-ZT + R and ZT-ZT preserved the lability of SOC, instead of oxidizing it towards more chemically recalcitrant pools. Overall, the increment in total SOC under ZT-ZT + R registered ~21% higher CPI over CT-CT. The CMI, which reflects the changes in SOC from initial status (Dey et al., 2020; Jat et al., 2019; Parihar et al., 2019), registered significant higher values under ZT-ZT and ZT-ZT + R than other treatments as a result of improvements in both labile and non-labile pools (Figure 5). Treatment ZT-ZT + R had almost the double values of CMI to that of CT-CT. The loss of labile C under PB-PB + R resulted in lower values of CMI, compared with ZT-ZT + R, despite similar C input.

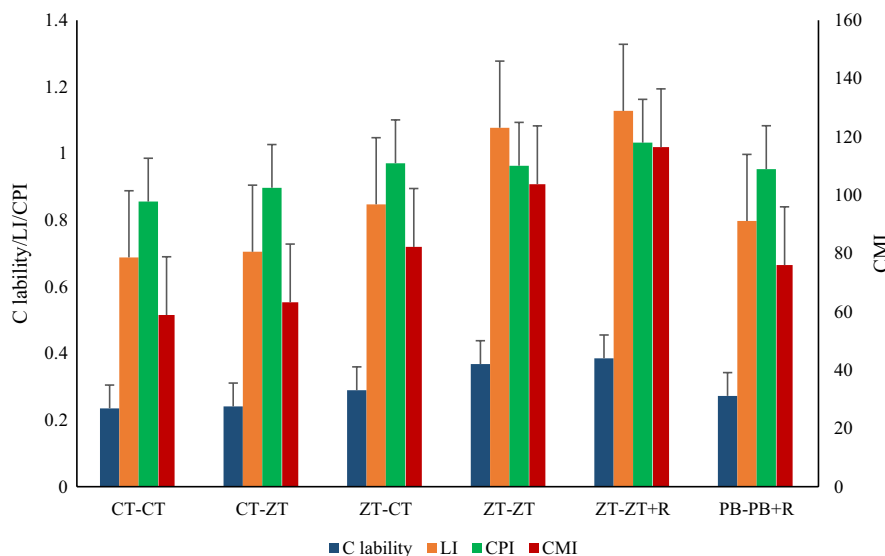


FIGURE 5 Changes in soil organic carbon (SOC) lability, lability index (LI), carbon pool index (CPI) and carbon management index (CMI) in 0–15 cm soil layer as affected by continuous conventional and CA practices over a 6-year period. CT-CT: Transplanted rice followed by conventional-till wheat; CT-ZT: CT rice followed by zero-till wheat; ZT-CT: ZT direct seeded rice followed by CT wheat; ZT-ZT: ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with residue retention of both crops; PB-PB + R, R-W system on permanent beds with residue retention for both crops. Error bars represent LSD ($p < .05$).

Apart from being itself a source of labile SOM, the retention of cereal residues in ZT-ZT + R enhanced the availability of mineralizable substrates, favouring microbial growth and activity (Table 3). Positive effect of residue retention on MBC was more pronounced than that of reduced tillage (Spedding et al., 2004); therefore, registering significant enhancement in MBC under ZT-ZT + R compared with ZT-ZT and all other crop residue removal plots (Table 3).

4.2 | Humic acids characteristics as affected by conservation agriculture

In the present study, the accumulation of fresh organic matter under ZT-ZT + R exceeded the capability of microbes to act on them for their humification or decomposition into CO_2 . Physical protection through soil aggregation was the major mechanism of C stabilization under ZT-ZT + R instead of chemical recalcitrance. Therefore, there was an abundance of HA typically rich in aliphatic compounds with lower semiquinone-type free radical concentration and lower percentage of aromatic C under ZT-ZT + R (Figure 2), representing less advanced stage of humification (González-Pérez et al., 2007; Zhang et al., 2011) (Table 4) in turn promoting higher lability of C under ZT-ZT + R. Despite having higher C content, the presence of chemically recalcitrant aromatic C is less prevalent under ZT-ZT + R. On the contrary, despite having similar C input, more exposure under PB-PB + R resulted in more humification

of SOM, in turn, less lability of C compared with that under ZT-ZT + R.

The treatment ZT-ZT + R registered the highest proportions of –OH groups, followed by PB-PB + R, whereas the conventionally tilled plots had lesser amounts of –OH groups (Datta et al., 2022). The heavy residue retention and lesser mechanical disturbance under ZT-ZT + R did not favour rapid oxidation, in turn not favouring the synthesis of O-alkyl and –COOH groups, thus reducing the oxidation state and polarity of the HA (Table 4), compared with CT-CT. Relatively more oxidized SOM was found under PB-PB + R compared with ZT-ZT + R. The ZT-ZT + R treatments registered greater proportions of aliphatic alkyl (C-H) groups. The lowest abundances of ketone and carboxyl groups under ZT-ZT + R, followed by PB-PB + R, indicated lesser formation of quinone and semiquinone-type functional groups under CA. On the contrary, the conventionally tilled plots promoted oxidative environments, in turn favouring oxidation and aromatization of HAs, leading to greater chemical recalcitrance of C (Datta et al., 2022; González-Pérez et al., 2007).

The prevalence of less humified SOM under ZT-ZT + R reflected into great enhancements of SOC_{VL} and SOC_{L} pools (Table 3), which, in turn, improved the lability of SOC (Figure 5). As a consequence, the LI was ~64% higher under ZT-ZT + R than CT-CT, whereas CPI was only higher by ~21% in the former treatment than the latter (Figure 5). Higher prevalence of HAs containing labile/reactive functional groups is indicative of greater quality of soil C and higher soil fertility (González-Pérez et al., 2007), as these often act as potent buffer sources

of several macro- and micro-nutrients. In the highly calcareous experimental soil, presence of labile SOM with abundance of reactive functional groups under ZT-ZT + R often invokes the possibility of solubilization of free CaCO_3 through reaction with organic acids, and probable leaching of soluble bi-carbonates to the lower soil layer, where the inorganic C cannot be readily re-emitted back to the atmosphere (Dey et al., 2020; Jacinthe et al., 2011).

4.3 | Changes in soil nitrogen with respect to soil organic carbon

The effect of residue retention on soil N was more prominent than that of tillage alteration (Table 4 and Figure 1). Adoption of CA resulted in greater macroaggregate formation, thus locking up additional N in intra-POM (Bhattacharyya et al., 2019). Continuous supply of fresh organic matter in residue-retained plots, especially under double residue retention, upsurges microbial activity, and even more soil N gets locked up in soil microbial biomass (Table 4). As a result, despite higher total soil N under ZT-ZT + R treatments, mineral N was lower than other treatments because of locking up of excess N within aggregates and also in microbial biomass (Table 4), suggesting 'progressive N limitation' (Johnson, 2006). This contention was further supported by positive correlations of total soil N with POM-N and SMB-N, whereas mineral N did not show significant relationship with any of the SOC and N pools. The locked-up N may serve as a buffer pool of N, which may benefit succeeding crops in times of high N demand.

4.4 | Effect of different moisture and temperature regimes on mineralization of soil organic carbon and nitrogen

In general, higher temperature enhances SOM mineralization because of temperature-mediated increase in physiological and bio-chemical reaction rate of microorganisms involved in the process (Gutiérrez et al., 2013; Jat et al., 2019; Parihar et al., 2019). On the contrary, field capacity moisture regime is the optimal condition for SOM mineralization. Poor supply of oxygen slowed down SOM decomposition under submergence. Initially, the C_t was higher under FC25, owing to optimum moisture compared with that of 2.5 cm standing water in SM35. In later periods, however, the effect of higher temperature (35°C) on microbial activity was possibly far greater than that of optimum moisture (field capacity), in turn registering higher C_t under SM35 compared

with FC25. The study conclusively proves the higher GHG emission potential of edaphic conditions prevalent during rice crop (SM35), compared with that during wheat crop (FC25). The ill effects of higher temperature on CO_2 emission surpass the reductive effects of submergence. There was a possibility of excessive gaseous loss of N through denitrification and slower SOM decomposition owing to poor oxygen supply under submergence which might have resulted in lower mineral N in SM35 than FC25. Higher losses of N through volatilization at elevated temperature and higher microbial requirement of mineral N at higher temperatures because of increased microbial activity could be the other possible reasons.

4.5 | Kinetics of soil organic carbon and nitrogen mineralization in relation to lability of C pools and humic acid

The first-order two-compartment model of SOM mineralization recorded much higher values of decay constants associated with labile pools of SOC and N mineralization, as compared to those associated with recalcitrant pools (Table 5), suggesting greater decay of labile SOM. Higher values of Kc1 and Kc2 were reported under SM35 than FC25 (Table 5), implying a temperature-mediated increase in decay rates of both labile and recalcitrant pools of SOC (Ghosh et al., 2019; Jat et al., 2019). Contrary to this, the decay rate constants associated with labile pools of N were similar under both hydro-thermal regimes. Furthermore, poor oxygen supply and possible N volatilization resulted in slower decay from recalcitrant N pools under SM35 compared with FC25.

Treatment ZT-ZT + R received massive amounts of organic C inputs under least mechanical disturbances. Abundance of less humified SOM with prevalence of aliphatic C and enhanced lability of SOC under ZT-ZT + R (Figure 5) provided a sizeable source of oxidisable substrate for consumption by an enhanced microbial biomass (Table 3), in turn resulting in high cumulative SOC mineralization (Figure 3) (Jat et al., 2019; Parihar et al., 2019). Despite a higher per se values of C_t (Figure 3), heavy residue-retained CA treatments (ZT-ZT + R and PB-PB + R) registered significantly lower decay rates of C mineralization compared with ZT-ZT under FC25 (Table 5). Under ZT-ZT + R, the SOM is more labile in nature, as is evident from lesser degree of humification (Table 4) and higher values of LI (Figure 5). Greater physical protection of labile SOC in the form of POM-C resulted in lower rates of C loss from relatively more labile pools under ZT-ZT + R as compared to CT-CT (Bhattacharyya et al., 2019; Jat et al., 2019).

TABLE 5 Effect of different moisture and temperature regimes on decay rates (Kc and Kn) ($\text{mg } 100\text{g}^{-1}\text{day}^{-1}$) of soil organic C and N mineralization.

Treatment	Decay rate constant of SOC mineralization				Decay rate constant of N mineralization			
	SM35		FC25		SM35		FC25	
	Kc1 ($\times 10^{-1}$)	Kc2 ($\times 10^{-4}$)	Kc1 ($\times 10^{-1}$)	Kc2 ($\times 10^{-4}$)	Kn1	Kn2 ($\times 10^{-4}$)	Kn1	Kn2 ($\times 10^{-4}$)
CT-CT	9.01a	11.4a	7.32a	8.85bc	10.0	2.61b	10.0	3.71bc
CT-ZT	9.10a	12.5a	7.77a	9.87b	10.0	1.96c	9.99	3.30c
ZT-CT	9.40a	12.5a	8.07a	10.1b	10.0	2.95b	10.0	3.87b
ZT-ZT	8.89a	12.5a	8.21a	12.1a	10.0	3.19b	10.0	4.11ab
ZT-ZT + R	8.91a	12.3a	2.06b	8.22c	10.0	4.49a	10.0	4.53a
PB-PB + R	8.87a	10.9a	2.48b	5.26d	10.0	2.18c	10.0	3.84bc
Mean	9.03	12.0	5.65	9.07	10.0	2.90	10.0	3.89

Note: Values within a column followed by the same letter are not significantly different at $p \leq .05$.

Abbreviations: CT-CT, transplanted rice followed by conventional-till wheat; CT-ZT, CT rice followed by zero-till wheat; FC25, incubation at 25°C under field capacity; Kc1, decay rate coefficient for the labile pool of SOC; Kc2, decay rate coefficient for the recalcitrant pool of SOC; Kn1, decay rate coefficient for the labile N; Kn2, decay rate coefficient for the recalcitrant N; PB-PB + R, R-W system on permanent beds with crop residue retention for both crops; SM35, incubation at 35°C under continuous submergence; ZT-CT, ZT direct seeded rice followed by CT wheat; ZT-ZT, ZT direct seeded rice followed by ZT wheat; ZT-ZT + R, ZT direct seeded rice followed by ZT wheat with crop residue retention of both crops.

Greater physical barrier between SOC and metabolizing microbes under ZT-ZT + R slowed down C decay despite its' enhanced lability.

The heavy CR load, accompanied by lesser decay rates of C mineralization under zero-till conditions, results in accumulation of labile C in the treatment (Table 3). These increments in labile C have great ramifications in sequestering and stabilizing C, as well as improving nutrient supplying capacity of soils. On the contrary, the effects of CA on N mineralization could not be explained very well from the above data set. To explain the kinetics of N dynamics in soil, volatilization and immobilization components need to be considered.

The present study necessitates on the implementation of full CA package of practices. Cultivation of tilled direct-seeded rice may lead to higher CO_2 emissions, because of optimal temperature and moisture conditions during *kharif* seasons. On the contrary, cultivation of ZT-ZT + R is ideal in reducing the CO_2 emission. The C input under heavy loads of CR retention coupled with ZT would potentially overwhelm the increase in C outputs and lead to betterment of soil organic C, both in terms of quantity and quality. This approach is a stepping stone towards a C-neutral and sustainable crop production system in sub-tropical Indian conditions.

5 | CONCLUSION

Conservation agriculture provided continuous external input of carbonaceous materials under the least mechanical disturbances. Under ZT-ZT + R, subsequent

improvement of both labile and non-labile SOC leads to a holistic enhancement of SOC. Similar increments were registered for soil N, as it is closely related to the dynamics of SOC. But the immediate availability of soil N may be hampered because of 'progressive N limitation', mainly caused by the encapsulation of mineral N forms in stable aggregates or immobilization in freshly formed microbial biomass. This fact also necessitates an urgent need for CA-specific N management protocol. The least mechanical disturbances under ZT-ZT + R promoted physical stabilization of SOM through soil aggregation. Greater abundance of less humified SOM enhances the oxidative/chemical lability of SOC and does not promote chemical recalcitrance through oxidative polymerization and subsequent formation of quinone and semiquinone type of reactive groups. The CA preserves the lability of SOM in a physically protected state, which not only provide us with a win-win situation of C stabilization, but also in a form which is more beneficial from a soil fertility perspective. In the present experimental soil, where the majority of SOC resides in non-labile form, adoption of CA improves the quality of SOC, through enhancements in lability. Greater abundance of non-mature SOM might prove extra beneficial in calcareous soil through solubilization of CaCO_3 and removal from surface layer. The physical stabilization of SOC under ZT-ZT + R inhibits C mineralization or loss to the atmosphere, promoting effective C sequestration under CA. The study also clearly registered that the effects of submergence in stabilizing SOM is rather inconsequential in the prevalent higher temperature range in the rice growing periods of eastern IGP, as compared to wheat

growing periods. These state a major concern for the impending global warming scenario, where a significant portion of SOC can be lost, which were generally stable under tropical RW systems. On the contrary, practising ZT along with crop residue retention proved to be beneficial in terms of stabilizing SOC through a reduction in decay rates of mineralization. The comparative study of different edaphic scenarios also cautions us about incomplete adoptions of the CA package of practices regarding C emissions. The zero-till conditions should not be disturbed in any time of the year if we want to unlock the full potential of CA regarding C stability/C sequestration. The optimum crop residue cover is imperative towards a C-neutral farming system, both as an input source of soil C, and as a barrier to C mission from the crop field.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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