



Sustainable Soil Management for Climate Resilience: Long-Term Management Effects on Soil Carbon Sequestration and Nitrogen Dynamics in a Semi-Arid Tropical *Inceptisol* of India

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Abstract

The injudicious use of synthetic agri-inputs has adversely influenced the soil fertility in tropical and subtropical agriculture with depleted reserves of carbon (C) and nitrogen (N). Assessing dynamics of these nutrient elements and their impacts on crop productivity in irrigated semi-arid cropping systems are immensely influenced by the climate induced crop nutrient responses. Therefore, to comprehend the fundamental mechanisms that govern the carbon and nitrogen dynamics in diverse nutrient management systems is crucial for understanding the effects of climate-induced variations in nutrient availability on crop yield. In this study, surface soil (0–15 cm) samples were collected from four different sources: 100% organic sources (T₁), 75% organic+25% inorganic sources (T₂), 50% organic+50% inorganic sources (T₃), and 100% inorganic sources (T₄). The samples were then subjected to analysis for C and N dynamics, along with C sequestration potential. The data was collected from the following cropping systems; rice-wheat-sesbania (CS₁) and rice-barley-green gram (CS₂). The soil potential for C sequestration exhibited a range of 0.18 to 0.02 Mg C ha⁻¹ yr⁻¹ in CS₁ and 0.17 to 0.03 Mg C ha⁻¹ yr⁻¹ in CS₂, respectively, across the soil nutrient treatments. The long-term addition of organic sources in organic ameliorations with or without inorganic fertilizers significantly enhanced active carbon and nitrogen pools compared to 100% inorganic nutrient treatment in both the cropping systems. The ammoniacal and nitrate nitrogen extracted from inorganic nutrient treated soils were higher than that of organic treatments. Subsequently, soils amended with organics had superior biological quality in terms of higher MBC, PmOC and MBN than other treatments. The higher sustainability yield index (~0.79) was recorded in organically amended soil among the cropping systems. The research findings demonstrate that the continuous incorporation of organic amendments for long-term is a beneficial approach for improving the dynamics of soil carbon and nitrogen in tropical soils.

Keywords Carbon/Nitrogen management index · C/N sequestration · Mineralization rate constant · Organic farming · Sustainability yield index · *Inceptisols*

1 Introduction

The management of Soil Organic Carbon (SOC) plays a vital role in the restoration of soil health, preservation of soil fertility, and sustenance of crop production (Tigga et al. 2020). Hence, SOC is frequently used as a primary indicator for evaluating soil health and quality (Jat et al. 2019). The decrease in SOC is a notable problem to the resilience of

agricultural production systems (Dey et al. 2018). Recent research studies (Tigga et al. 2020) indicated that most of the Indian soils have deficient levels of SOC (0.3 to 0.4%) which is responsible for reduced soil health and declined crop production. In the region of Indo-Gangetic plains (IGP), imbalanced fertilizer application and ongoing non-scientific practices of rice-wheat system have led to the deterioration of SOC in soil, declined soil health, water and energy

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use efficiency, increased greenhouse gas emission (Das et al. 2018; Dey et al. 2018; fagodiya et al., 2023). Also, the imprudent utilization of synthetic agricultural inputs, such as fertilizers and plant protection chemicals, has led to unfavourable consequences on soil fertility within tropical and subtropical farming. This has led to a reduction in the reserve sources of carbon (C) and nitrogen (N) (Lal 2021) are essential for upholding healthy soil and facilitating crop growth (fagodiya et al., 2019). These conventional RWCS intensive farming methods lend enough validation for the adoption of strategies that stimulate the combining of various nutrient sources and the pursuit of new and improved methods of crop diversification. Hence, the identification of mitigation measures is imperative in the development of a sustainable agricultural industry and the reformation of land use policies (Pachauri et al. 2014; Zani et al. 2023). Several scientific reports have elaborated the affirmative impacts of integrated nutrient management and crop diversification on higher system yields, improved soil health, lower GHG emission and potential resource savings in current scenario (Jat et al. 2018; Gupta et al. 2019; Dutta et al. 2022; Meena et al. 2022). Several agricultural management strategies i.e., residue/compost turnover, use of organic amendments, Integrated Nutrient Management (INM) exerts a significant impact on soil carbon and nitrogen dynamics (Ansari et al. 2022). Soil organic carbon pools are the early indicators of soil health (Zhang et al. 2020). Therefore, the assessment of SOC pools will be helpful in achieving soil quality and sustained crop yields (Awale et al. 2017; Nath et al. 2017).

According to reports, exopedonic elements such as crop diversification, nutrient inputs, soil and crop management strategies, and the integration of organic along with inorganic nutrient sources are key determinants of the sequestration of carbon and nitrogen in agricultural soils. (Kumar et al. 2017; Lal 2018; Meena et al. 2022). There exists a correlation among soil organic carbon (SOC) and various soil bio-physical and chemical attributes, alongside the release and uptake of plant-available nutrients and nutrient cycle, making it an insightful measure of soil fertility and sustainability of agriculture. In the terrestrial ecosystem, SOC is possibly considered the largest storage for atmospheric carbon dioxide (CO₂), and it acts as an insightful determinant of crop productivity and soil fertility (Babu et al. 2020). The positive relationship between SOC content and crop yield can be reflected by the higher crop productivity. Studies have shown that the transition of non-organic soil to an organic production system may result in increased C sequestration and other nutrient contents, along with improved soil quality (Gattinger et al. 2012; Das et al. 2013).

The management of soil organic carbon significantly impacts soil quality, long-term fertility, and production capacity (Zhou et al. 2010; Glenk et al. 2017). In this

particular context, it has been documented that the implementation of organic nutrient management practices yields greater soil ecosystem services in comparison to chemical nutrient practices (Reganold and Wachter 2016). The organic nutrient management practices can sequester soil organic carbon to the extent of $0.45 \pm 0.21 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the surface soil and higher potential for storing and improving the nutrients contents as compared to the traditional systems (Gattinger et al. 2012; Cavigelli et al. 2013; Francaviglia et al. 2023). Thus, suitable agronomic practices along with improved nutrient management to reduce carbon losses and/or enhance in soil SOC stock are highly required. These practices are: application of organic amendments, crop diversification with inclusion of legumes, improved crop varieties, green manures and deep-rooted crops with higher below ground biomass coverage, and unplanted fallow lands etc. Thus, intensification and re-designing of cropping sequence with suitable legumes and other biomass crops could be helpful in enhancing carbon and nitrogen pools and improving quality of soil (e.g., Carbon and nitrogen management indexes—CMI and NMI, and soil biological attributes). The SOC and N pools, CMI and NMI, carbon and nitrogen sensitivity indexes, and soil biological attributes are considered as the prime indicators of soil health, due to their significant influence on crop production and environment.

Soil microbial biodiversity (microbial biomass carbon, nitrogen and enzyme activities) serves as a fundamental cornerstone of a sustainable agriculture production system (Babu et al. 2020). Detecting short and medium-term variations in total soil organic carbon (TSOC) and total nitrogen (TN) induced by agronomic and nutrient management can be challenging due to the high variability in non-labile fractions of these nutrients. (Blair et al. 2006; Gong et al. 2011). The SOC - labile fractions (C_{VL}-very labile C, and C_L-labile C) and nitrogen indicators (Microbial biomass nitrogen, mineral N) are highly responsive to soil and nutrient management practices (Nandan et al. 2019; Meena et al. 2022). These fractions are considered as initial and sensitive indicators of SOC and N. The relative proportion of labile C (C_{VL}, C_L, MBC, POC) and N (MBN and mineral N) are crucial factors in terms of C and N dynamic, and soil quality. The degradability of soil organic carbon and nitrogen may not always align with their chemical properties. Therefore, the assessment of unstable carbon and nitrogen fractions could be a more rigorous approach to evaluate the impact of management practices, such as crop diversification and legume incorporation, on soil quality in organic agriculture. The development of the carbon and nitrogen pool index (CPI and NMI) and C and N sensitivity indexes has been based on alterations in diverse C and N fractions. These indexes are utilized to assess the enhancement in soil

quality resulting from management practices. (Blair et al. 2006; Gong et al. 2011). Therefore, it is recommended that the CMI and NMI, which have been derived from the concept of lability, are the most effective means for quantitatively assessing soil quality (Blair et al. 2006). The CMI and NMI is considered as an indicator of shift in soil quality due to different nutrient management practices, and therefore, effective soil degradation mitigation practices can be evaluated (Moharana et al. 2012; Ghosh et al. 2016). Numerous studies have demonstrated the advantageous outcomes of various soil management techniques. However, some fundamental questions and state-of-the-art remained unexplained i.e. (i) the general importance of nutrient management on soil carbon fractions and nitrogen pools in the context of mitigating climate change; (ii) how and where soil carbon and nitrogen concentrations may change due to these practices, and how carbon fractionation and nitrogen pools may help on understanding C and N permanence in soil; (iii) importance of nutrient management strategies and crop diversification under the study and (iv) how (i-iii) may lead to a better understanding of additional soil C and N accrual and permanence (sequestration) as dependent of crop diversification and nutrient management strategies in

the system studied. We hypothesized that carbon fractions and nitrogen pools could be a critical factor for improving C and N storage with these objectives: (i) to quantify the C and N fractions (ii) to measure the best nutrient treatment and cropping sequence in organic farming.

2 Materials and methods

2.1 Study Area Description

The experimental site is situated at the Research Farm (29°4'37.36"N, 77°42'15.70"E, 230 m.s.l.) of ICAR-Indian Institute of Farming Systems Research, Modipuram of Meerut District, Uttar Pradesh State, India (Fig. 1). The area located in the northern part of the Indian Subcontinent has a semi-arid tropical continental monsoon climate with average maximum and minimum temperatures of 40 °C and 7.8 °C, respectively, and annual precipitation cumulative 823 mm. Approximately 90% of the region's annual precipitation occurs between July and October, with usual drought conditions during winter and spring seasons. The soil is classified as sandy loam, an Ust-ochric *Inceptisol* (*Typic Ustochrept*

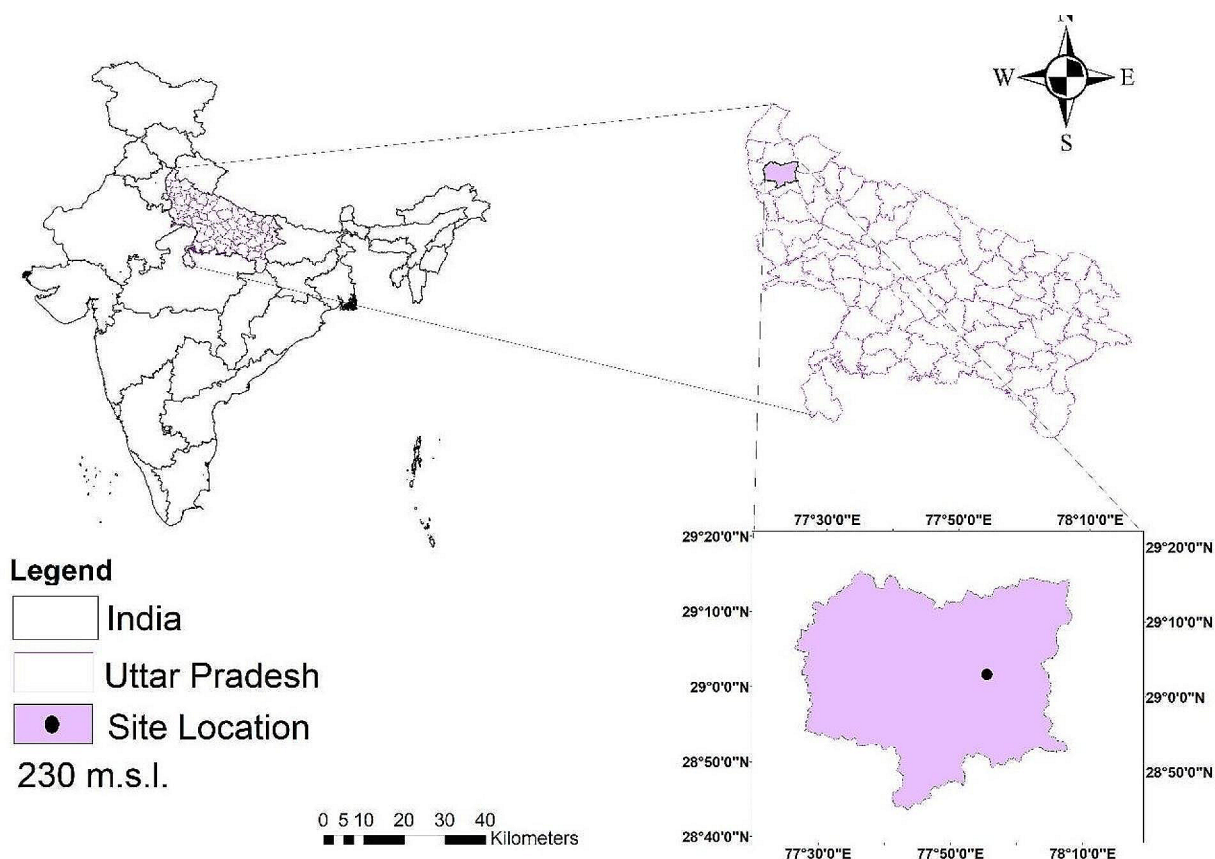


Fig. 1 Map showing study site in the Indo-Gangetic Plains

Table 1 Impacts of diverse nutrient management and diversified cropping on SOC, ρ_b and C: N ratio after seventeen cropping cycles

Treatments	SOC (g kg^{-1})		Mean	ρ_b (g cm^{-3})		Mean	C: N	
	CS ₁	CS ₂		CS ₁	CS ₂		CS ₁	CS ₂
Initial soil = 3.10			Initial soil = 1.62					
T ₁	8.62 ± 0.91 ^a	8.26 ± 0.62 ^b	8.44 ^A	1.30 ± 0.14 ^g	1.35 ± 0.09 ^f	1.33 ^D	23.95	23.53
T ₂	7.49 ± 0.53 ^d	7.62 ± 0.81 ^c	7.56 ^B	1.39 ± 0.12 ^e	1.41 ± 0.04 ^d	1.40 ^C	24.31	24.26
T ₃	6.95 ± 0.35 ^f	7.00 ± 0.37 ^e	6.98 ^C	1.47 ± 0.21 ^c	1.46 ± 0.04 ^c	1.47 ^B	25.05	24.4
T ₄	6.46 ± 0.28 ^g	6.38 ± 0.32 ^h	6.42 ^D	1.51 ± 0.32 ^b	1.53 ± 0.6 ^a	1.52 ^A	25.31	24.54
Mean	7.38 ± 0.49 ^A	7.32 ± 0.48 ^B		1.42 ± 0.20 ^B	1.44 ± 0.04 ^A			

T₁: 100% organic; T₂: 75% organic + 25% inorganic; T₃: 50% organic + 50% inorganic; T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-sesbania; CS₂: Rice-barley-green gram; SOC: soil organic carbon; ρ_b : bulk density; C:N: Carbon nitrogen ratio. Different lower case (a to h) and upper case (A to D) letters within rows and columns indicate that they are significant at $P < 0.05$ as per the DMRT

in the USDA system). The initial soil sample in the plough layer collected during the initiation of the experiment in the year 2004 had the following initial physico-chemical attributes: pH 8.32 (1:2.5 soil: water); electrical conductivity (EC) 0.42 dS m⁻¹, soil organic carbon (SOC) 3.10 g kg⁻¹, available nitrogen (N) 164.7 kg ha⁻¹, Olsen's phosphorus (P) 8.47 mg kg⁻¹, available potassium (K) 98 kg ha⁻¹ (Appendix Table 1).

2.2 Experimental Design and Management

Prior to June 2004, rice-wheat was grown as a monoculture at the experimental site with 100% inorganic nutrient management. To spur carbon sequestration and nitrogen dynamics, the field has been diversified with two cropping systems since 2004. (i) rice-wheat-sesbania (CS₁), (ii) rice-barley-green gram (CS₂) along with four different nutrient treatments: 100% organic (T₁), 75% Organic + 25% inorganic (T₂), integrated (50% organic and 50% inorganic sources) (T₃), and 100% inorganic (inorganic fertilizers) (T₄). The treatments were set in a plot size of 7 × 6 m (each plot) in a completely randomized block design. A gap of 1.5 m was maintained between separate nutrient treatment plots, and individual plots were prepared with power tiller throughout each cropping season. This was done to prevent the capillary movement of nutrients, organic manures, and compost from one treatment plot to another, as well as any intermixing of the added inputs. The detailed information about the types and amount of inputs applied, and application methods are provided in Appendix Table 2. The nutrient composition of farm yard manure (FYM) and vermicompost (VC) was 27.7% and 23.2% C, 0.73% ± 0.03 and 1.3% ± 0.04 N, 0.24 ± 0.06 and 0.89% ± 0.04 P₂O₅, 0.60 ± 0.05 and 1.2% ± 0.03 K₂O, respectively. All the recommended National Programme for Organic Production (NPOP) protocols were strictly adhered to for Organic, integrated and inorganic management (Appendix Table 3). The rice crop in cropping systems, was harvested in the first fortnight of November every year. Details of the cropping seasons of different crops during the study is illustrated in (Fig. 2).

2.3 Crop Harvesting and Biomass Measurement

Plot wise crops were harvested manually. The grain yield of rice, wheat, and barley was observed to possess a moisture content of 12%. Summer green gram was cultivated to add the addition yield and easily decomposable biomass. As a green manure crop, entire biomass of sesbania was tilled into the soil using a power tiller approximately 40–45 days after sowing.

2.4 Soil Sampling and Processing

Triplicated surface soil samples (0–15 cm depth) were collected at the harvest of rabi season crops in the year 2023 from each plot after 17 crop cycles. To calculate the gravimetric moisture content and bulk density (ρ_b) (Blake and Hartge 1986), core sampler was used and samples were weighed in the laboratory both before and after oven drying at a temperature of 105 ± 1 °C for 24 h. The replicated soil samples were divided into two segments. The first part was stored at a temperature of 4 °C for the purpose of measuring the biological parameters. The second portion was subjected to air-drying under ambient conditions of 25 °C. The clods were subsequently disintegrated, and extraneous materials such as stones, plant residues, and roots were eliminated. The sample was then passed through a 2 mm sieve. The processed samples were stored in vacuum-sealed plastic bags for the purpose of analysing different soil organic carbon fractions and nitrogen pools.

2.5 Analysis of Carbon Fractions and Nitrogen Pools

The estimation of soil organic carbon (SOC) content was conducted through the wet oxidation method, which was outlined by Walkley and Black (1934). Automatic elemental analyzer (Euro Vector; Elemental analyser) was utilized to determine total organic carbon (TOC) after removing the inorganic C from the sample with the help of dilute 1 N HCl. Active organic C (PmOC) in soil was determined according to Blair et al. (1995). Organic C fractions having different

Table 2 Impacts of long-term nutrient management practices and diversified cropping on various organic carbon fractions after seventeen cropping cycles

Treatments	C _{VL} (g kg ⁻¹)		C _L (g kg ⁻¹)		C _{LL} (g kg ⁻¹)		C _{NL} (g kg ⁻¹)		Mean	
	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂
T ₁	3.62±0.25 ^a	3.35±0.52 ^b	1.02±0.06 ^a	1.00±0.08 ^b	1.01 ^A	1.00±0.08 ^b	3.98±0.61 ^a	3.91±0.73 ^b	10.73±1.56 ^b	11.18±1.21 ^a
T ₂	3.21±0.41 ^c	2.91±0.21 ^c	1.00±0.02 ^b	0.98±0.04 ^c	0.99 ^A	0.98±0.04 ^c	3.28±0.81 ^e	3.73±0.58 ^c	9.66±1.02 ^d	9.75±0.96 ^c
T ₃	2.92±0.31 ^d	2.84±0.31 ^f	0.85±0.02 ^d	0.85±0.02 ^d	0.85 ^B	0.85±0.02 ^d	3.18±0.61 ^f	3.3±0.46 ^d	9.58±1.11 ^e	9.49±0.99 ^f
T ₄	2.71±0.19 ^g	2.59±0.34 ^h	0.75±0.01 ^f	0.77±0.02 ^e	0.76 ^C	0.77±0.02 ^e	3.00±0.42 ^h	3.02±0.31 ^g	8.86±0.96 ^h	9.00±0.83 ^g
Mean	3.12 ^A	2.92 ^B	0.91 ^A	0.90 ^B			3.36 ^B	3.49 ^A	9.71 ^B	9.86 ^A

T₁: 100% organic; T₂: 75% organic + 25% inorganic; T₃: 50% organic + 50% inorganic; T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-seabania; CS₂: Rice-barley-green gram C_{VL}: Very labile carbon; C_L: labile carbon; C_{LL}: less labile carbon; C_{NL}: Non-labile carbon. Different lower case (a to h) and upper case (A to D) letters within rows and columns indicate that they are significant at $P < 0.05$ according to DMRT

oxidizability i.e., very labile (C_{VL}), labile (C_L), and less-labile (C_{LL}) were examined using the modified Walkley and Black method as described by Chan et al. (2001).

- C_{VL} (very labile carbon): C oxidized by K₂Cr₂O₇ by 12 N H₂SO₄ (0.5:1 acid: aqueous solution ratio);
- C_L (labile carbon): C oxidized by K₂Cr₂O₇ by 18 N H₂SO₄ (1:1 acid: aqueous solution ratio) - C oxidized by K₂Cr₂O₇ by 12 N H₂SO₄;
- C_{LL} (less-labile carbon): C oxidized by K₂Cr₂O₇ by 24 N H₂SO₄ (2:1 acid: aqueous solution ratio) - C oxidized by K₂Cr₂O₇ by 18 N H₂SO₄;
- C_{NL} (non-labile carbon): Total organic carbon (TOC) - C oxidized by K₂Cr₂O₇ by 24 N H₂SO₄;

These analyzed carbon fractions were divided into two groups as:

- Active carbon pools (AC): C_{VL} + C_L.
- Passive carbon pools (PC): C_{LL} + C_{NL}.

The estimation of available nitrogen was conducted through the utilization of alkaline permanganate (KMnO₄), as per the methodology outlined by Subbiah and Asija (1956). The process of Keeney and Nelson (1982) and Waring and Bremner (1964) was followed for estimation of NH₄⁺-N and NO₃⁻-N content in soil sample using a micro-Kjeldahl steam distillation. The measurement of Potential Mineralizable N (PMN) in soil was conducted in accordance with the protocol outlined by Waring and Bremner (1964). Soil N fractions (labile and non-labile fractions) were analyzed by using the standard protocol (Blair et al. 1995; Westerhof et al. 1998). Microbial biomass nitrogen (MBN) was quantified by the fumigation and non-fumigation extraction methods (Brookes et al. 1985) and Microbial biomass carbon (MBC) (Vance et al. 1987) in soil samples as described by Jenkinson and Powlson (1976).

2.5.1 C and N Mineralization Study

C and N mineralization in soil were investigated separately, as described by Angers and Recous (1997). A first-order kinetic equation was used to calculate the amount of CO₂ emitted throughout the soil incubation period (Mohanty et al. 2013).

The C_{VL} + C_L content in soil was taken as potentially mineralizable C (C₀) in equation-1 and PMN value was taken as potential mineralizable nitrogen (N₀) in equation (2).

$$C_{\min} = C_0 (1 - e^{-kt}) \quad (1)$$

Table 3 Impacts of diverse nutrient management and diversified cropping on $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and Non-labile-N after seventeen cropping cycles

Treatments	$\text{NH}_4^+\text{-N}$ (mg kg ⁻¹)		Mean	$\text{NO}_3^-\text{-N}$ (mg kg ⁻¹)		Mean	Non-labile-N (mg kg ⁻¹)		Mean
	CS ₁	CS ₂		CS ₁	CS ₂		CS ₁	CS ₂	
T ₁	24.25 ± 2.92 ^e	23.43 ± 1.98 ^f	23.84 ^D	15.48 ± 1.81 ^f	15.51 ± 1.61 ^f	15.50 ^D	0.481 ± 0.02 ^a	0.482 ± 0.01 ^a	0.48 ^A
T ₂	24.43 ± 3.21 ^d	24.37 ± 2.51 ^e	24.40 ^C	15.80 ± 1.45 ^e	15.93 ± 1.41 ^d	15.87 ^C	0.452 ± 0.02 ^a	0.451 ± 0.03 ^a	0.45 ^A
T ₃	25.08 ± 3.62 ^c	24.60 ± 1.74 ^d	24.84 ^B	16.34 ± 1.73 ^c	16.41 ± 1.61 ^c	16.37 ^B	0.443 ± 0.01 ^a	0.450 ± 0.02 ^a	0.44 ^A
T ₄	26.15 ± 2.51 ^a	25.34 ± 2.41 ^b	25.75 ^A	17.04 ± 1.79 ^b	17.27 ± 1.29 ^a	17.15 ^A	0.434 ± 0.01 ^a	0.432 ± 0.01 ^a	0.42 ^A
Mean	24.98 ^A	24.44 ^B		16.17 ^B	16.28 ^A		0.452 ^A	0.453 ^A	

T₁: 100% organic; T₂: 75% organic + 25% inorganic; T₃: 50% organic + 50% inorganic; T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-sesbania; CS₂: Rice-barley-green gram; NH_4^+N : Ammonical nitrogen; NO_3^-N : Nitrate nitrogen. Different lower case (a to h) and upper case (A to D) letters within rows and columns indicate that they are significant at $P < 0.05$ according to DMRT

Month	July		August		September		October		November		December		January		February		March		April		May		June	
Fortnight	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
R-W-S	Rice								Wheat								Sesbania							
R-B-GG	Rice								Barley								Green gram							

Fig. 2 Duration of different crops in high frequency cropping sequences under different nutrient management. R-W-S: rice-wheat-Sesbania; R-B-GG: Rice-wheat-green gram

$$N_{\min} = N_0 (1 - e^{-kt}) \quad (2)$$

C_{\min} and N_{\min} are the amount of C and N mineralized at any specific time t (day) respectively, k is first-order rate constant (day⁻¹).

C and N half-life were calculated as follows (Samra et al. 2017)

$$\text{Half life} = \frac{0.693}{k} \quad (3)$$

2.6 Computation of C and N Indices

2.6.1 Carbon Management Index (CMI)

The equation developed by Blair et al. (1995) was used to calculate CMI considering the nearby uncultivated soil a reference:

$$\text{CMI} = \text{LI} \times \text{CPI} \times 100 \quad (4)$$

Where, LI and CPI represent the lability index and carbon pool index, respectively as per Blair et al. (1995).

The LI and CPI were quantified as the follows:

$$\text{Lability of C} = \frac{C_L}{C_{NL}} \quad (5)$$

C_L is the C fraction oxidized by KMnO_4 and C_{NL} is the C remained unoxidized by KMnO_4

$$\text{LI of C} = \frac{\text{Lability of C in sample soil}}{\text{Lability of C in reference soil}} \quad (6)$$

$$\text{CPI} = \frac{\text{Sample TOC}}{\text{Reference TOC}} \quad (7)$$

Where; TOC = Total organic carbon in samples and Initial soil.

2.6.2 Nitrogen Management Index (NMI)

The mathematical formula developed by Gong et al. (2011) were used for calculating NMI, which follows similar line to CMI (Blair et al. 1995):

$$\text{NMI} = \text{LI} \times \text{NPI} \times 100 \quad (8)$$

where LI is the lability index of N and NPI is N pool index.

The lability index (LI) of N was calculated as follows:

$$\text{Lability of N} = \frac{\text{LBN}}{\text{NLN}} \quad (9)$$

Table 4 Impacts of diverse nutrient management and diversified cropping on active carbon, potential mineralizable nitrogen, microbial biomass carbon and microbial biomass nitrogen after seven cropping cycles

Treatments	PmOC (g kg ⁻¹)		PMN (mg kg ⁻¹)		MBC (mg kg ⁻¹)		Mean		MBN (mg kg ⁻¹)		Mean	
	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂
T ₁	1.21±0.03 ^b	1.25±0.02 ^a	30.92±3.21 ^b	31.08±2.26 ^a	31.00 ^A	483.21±12.46 ^b	503.99±37.15 ^a	493.60 ^A	46.46±9.12 ^b	48.07±9.12 ^a	47.27 ^A	
T ₂	1.11±0.02 ^d	1.12±0.01 ^c	29.37±2.51 ^d	29.74±2.13 ^c	29.56 ^B	366.65±31.62 ^d	371.26±27.31 ^c	368.96 ^B	44.86±5.17 ^d	46.11±6.16 ^c	45.48 ^B	
T ₃	0.98±0.01 ^f	1.01±0.02 ^e	26.21±2.61 ^e	27.54±3.10 ^e	26.88 ^C	334.67±24.52 ^f	344.00±20.71 ^e	339.33 ^C	42.95±2.21 ^e	44.59±8.61 ^e	43.77 ^C	
T ₄	0.88±0.01 ^h	0.93±0.01 ^g	25.67±2.14 ^h	26.37±2.61 ^f	26.02 ^D	327.67±29.17 ^g	335.52±25.15 ^f	331.59 ^C	41.55±1.31 ^h	43.69±6.98 ^f	42.62 ^D	
Mean	1.05 ^B	1.08 ^A	28.04 ^B	28.68 ^A	28.68 ^A	378.05 ^B	388.69 ^A	388.69 ^A	43.96 ^B	45.61 ^A	45.61 ^A	

T₁: 100% organic; T₂: 75% organic + 25% inorganic; T₃: 50% organic + 50% inorganic; T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-sesbania; CS₂: Rice-barley-green gram; PmOC: active carbon; PMN: potential mineralizable nitrogen; MBC: Microbial biomass carbon; MBN: microbial biomass nitrogen. Different lower case (a to h) and upper case (A to D) letters within rows and columns indicate that they are significant at $P < 0.05$

Where; LBN is the N fraction oxidized by KMnO₄ (labile N); and NLN is the N fraction remained unoxidized by KMnO₄ (total N– labile N)

$$Lability\ index\ of\ N = \frac{Sample\ soil\ lability}{Reference\ soil\ lability} \quad (10)$$

2.6.3 C and N Sensitivity Index (SI)

The calculation of the (SI) for different carbon (C) fractions and nitrogen (N) pools was performed based on the percentage change observed in SOC fractions and N pools resulting from diverse nutrient management treatments, utilizing the formula outlined by Banger et al. (2010).

$$SI = \frac{(Cf_{treatment} - Cf_{control})}{Cf_{control}} \times 100 \quad (11)$$

Where; Cf_{treatment} is the SOC fractions and N pools in the soil of a given treatment and Cf_{control} is the SOC fractions and N pools of Initial soil.

2.7 Computation of System Productivity

$$SP\ (tha^{-1}) = [RGY\ (tha^{-1}) + \frac{WGY\ (tha^{-1}) \times MSP\ of\ Wheat\ (US\$t^{-1})}{MSP\ of\ rice\ (US\$t^{-1})} + \frac{MGY\ (tha^{-1}) \times MSP\ of\ mungbean\ (US\$t^{-1})}{MSP\ of\ rice\ (US\$t^{-1})}] \quad (12)$$

Where, SP: system productivity; RGY: rice grain yield; WGY: wheat grain yield; MSP: minimum support price for the crops; MGY: mungbean grain yield. The minimum support price was taken for the year 2022–2023 fixed by the Commission for Agricultural Costs and Prices (CACP) Government of India. Rice MSP: 26.59 US\$ (in the year 2023).

The exchange rates existing on 01 September, 2015, 2016, 2017, 2018, 2019, 2020, 2021 and 2022 (X-rates, 2022) were taken for translating Indian Rupees (INR) to US Dollar (US\$).

2.7.1 Sustainability Yield Index

The sustainability yield index (SYI) of the experiment was developed using the mathematical formula outlined by Singh et al. (1990) and Saha et al. (2022):

$$SYI = \frac{(Y - \sigma)}{Y_{max}} \quad (13)$$

In this equation, Y represents the rice equivalent yield of the treatment, σ denotes the standard deviation of the treatment, and Y_{max} signifies the maximum rice equivalent yield observed in the experiment across years.

$$\text{Coefficient of variation (CV)} = \left(\frac{\sigma}{Y} \right) \times 100 \quad (14)$$

Where; σ is standard deviation of the treatments over the years and Y is the rice equivalent yield of the treatments over the years (t ha^{-1}).

2.8 Statistical Analysis

Necessary data of soil C and N pools and characteristics were evaluated by analysis of variance (ANOVA) using Windows-based SAS 9.4 (SAS Institute, 2003). Duncan's multiple range test (DMRT) was performed at $P \leq 0.05$ level to compare the individual treatment means. Correlation coefficients were used to assess the relationship among different fractions of C and N to crop productivity, CMI, NMI, and C stocks in the soil were analyzed using R package (R 4.1.2 version). Similarly, regression equations were also formulated in R package to evaluate the relationships between C and N in soil.

3 Results

3.1 Agronomic Productivity and Sustainability Yield Index (SYI)

The system productivity (SP) in terms of rice equivalent yield (REY) (average of seven years) of both the cropping systems varied significantly under different nutrient treatments. The treatments consisting of 100% organic nutrient management exhibited a SP increase of 7.68% and 4.97% in CS_1 and CS_2 , respectively, when compared to treatments consisting of 100% inorganic materials in both cropping systems. (Appendix Table 4). Likewise, 13.35% and 18.32% higher SP was observed in plots treated with 75% organic nutrient sources along with 25% inorganic nutrient sources over the 100% inorganically treated plots in CS_1 and CS_2 , respectively (Appendix Table 4). The utilization of the coefficient of variance (CV) and sustainability yield index (SYI) serves as a means of identifying and characterizing crop grain stability and sustainability. The findings of the current investigation suggest that the system productivity (SP) in terms of rice equivalent yield (REY) exhibited a reduced

coefficient of variation (CV) in plots treated with 100% organic and 75% organic combined with 25% inorganic nutrient sources, in comparison to plots treated with 100% inorganic sources, across both cropping systems. (Appendix Table 4). The SYI of 100% organically treated plots were 13.91% and 23.23% higher over the 100% inorganic nutrient treatments in CS_1 and CS_2 , respectively. Correspondingly, treatments with 75% organic and 25% inorganic nutrient sources also recorded 18.47% and 23.47% higher SYI compared to 100% inorganic treatments both in CS_1 and CS_2 , respectively.

3.2 Soil Bulk Density (pb)

The bulk density (pb) exhibited significant variations across different nutrient treatments in both the cropping systems. Overall, the bulk density values observed in plots treated with 100% organic and 75% organic methods were lower than those treated with 100% inorganic nutrients. Among the nutrient treatments, T_4 (100% inorganic) exhibited the highest pb value of (1.52 Mg m^{-3}), whereas the T_1 treatment (100% organic) recorded the lowest density of (1.33 Mg m^{-3}). In terms of percent decrease of pb of soil in different nutrient treatments over the initial condition (collected at the start of experiment in 2004) T_1 , T_3 , T_2 , and T_4 treatments recorded 17.9%, 13.6%, 9.3%, and 6.2% lower pb over the Initial soil, respectively (Table 1).

3.3 Total Soil Organic C and N; C:N Ratio

The continuous long-term application of organic and/or inorganic nutrient amendments resulted in a significant improvement ($p < 0.05$) in the total soil organic carbon and nitrogen levels. Among the long-term nutrient treatments implemented, the 100% organic treatment exhibited the highest levels of TOC and TON, followed by 75% organically treated soils (Fig. 3). The soil treated with 100% inorganic fertilizers exhibited notably higher levels of TOC and TON compared to the Initial soil. The higher nutrient build-up, in terms of TOC and TON were recorded in 100% organic and 75% organic treatments over the 100% inorganic treatment. The total organic carbon (TOC) levels exhibited a substantial increase of 86.5% and 58.8% for the 100% organic and 75% organic treatments, respectively. Similarly, the integrated and 100% inorganic plots showed a rise of 65.9% and 47.5% in TOC levels when compared to the Initial soil. The results indicate that soils treated with 100% organic nutrients exhibited a 26% and 32% increase in total organic carbon (TOC) and total organic nitrogen (TON) over the 100% inorganic treatments in both cropping systems, respectively. The TON values in T_1 , T_3 , T_2 , and T_4 treatments were respectively 63%, 43%, 34%, and 24%

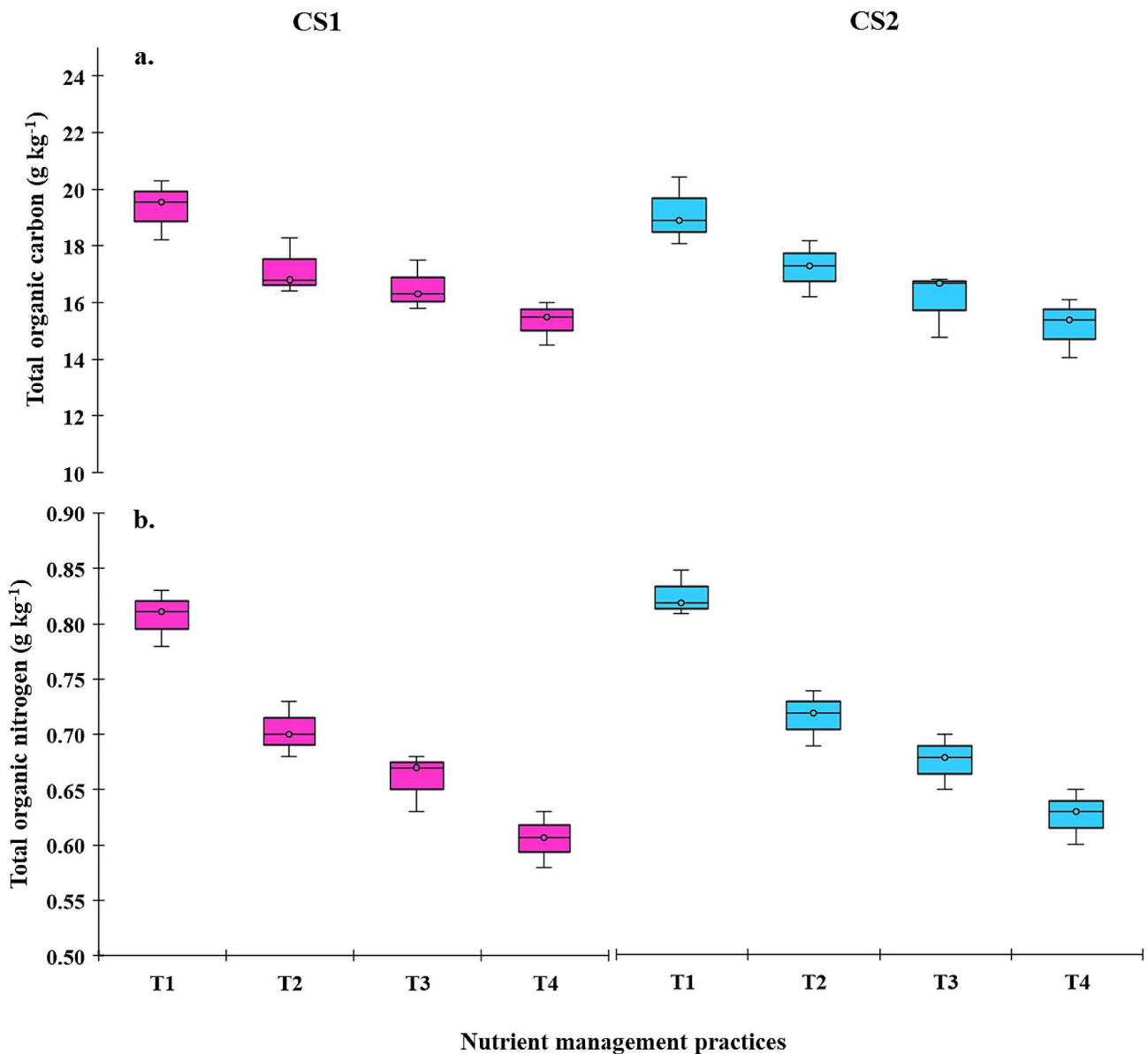


Fig. 3 Interactive effects of long-term nutrient management and diversified cropping on total organic carbon (TOC) and total organic nitrogen (TON). T₁:100% organic, T₂:75% organic+25% inorganic, T₃:

50% organic+50% inorganic, T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-sesbania, CS₂: Rice-barley-green gram

higher than the Initial soil (Fig. 3). The C: N ratio ranged from 23.95 to 25.31, and 23.53–24.54 was registered in CS₁ and CS₂, respectively (Table 1). 100% inorganic treatment (T₄) accounted for highest C: N ratio in both the cropping systems compared to other nutrient treatments. Although no significant differences were observed between the cropping systems.

3.4 Soil Organic Carbon and Various C Fractions

The seventeen consecutive years of adoption of organic amendments, with or without inorganic fertilizers, recorded significant impact on soil organic carbon (SOC) content. In comparison to the Initial soil (3.1 g kg⁻¹), a higher SOC content of 8.44 g kg⁻¹ (T₁) and 7.56 g kg⁻¹ (T₂) was recorded. Irrespective of cropping systems, the SOC concentration was 31.5%, 17.8%, and 8.7% higher in T₁, T₂, and T₃ compared to the 100% inorganic treatment, respectively (Table 1). The continuous incorporation of different soil

nutrient amendments significantly influenced the dynamics of SOC fractions. Application of 100% organic amendments (T_1) increased C_{VL} by 14.1%, 21.1%, and 31.7% as compared to 75% organic (T_2), INM (T_3), and 100% inorganic (T_4) nutrient application, respectively as stated in Table 2. Likewise, all the organic nutrient treatments with or without inorganic sources recorded 147.5%, 117.0%, 104.3%, and 87.9% higher C_{VL} content compared to the initial soil, respectively. Among the cropping systems, CS_1 had 6.9% higher C_{VL} in comparison to CS_2 in all the treated plots. For organic amendments treated plots with or without inorganic fertilizers, the C_L content varied significantly from 1.01 g kg^{-1} in 100% organic treatment (T_1) to 0.76 g kg^{-1} in 100% inorganic soils (T_4). The C_L content of each soil treatment was significantly influenced by nutrient sources, with higher value in organic amendment applied plots (Table 2).

Subsequently, 100% organic amendment application in CS_1 recorded higher C_{LL} (3.98 g kg^{-1}) over the same treatment of CS_2 (3.91 g kg^{-1}), however, 75% organic, INM and 100% inorganic treatments of CS_2 observed higher C_{LL} over the same treatments of CS_1 (Table 2). In both the cropping systems, 100% organically amended soils (T_1), recorded 22.7, 12.9 and 14.9% higher non-labile carbon (C_{NL}) content over 75% organic (T_2), INM (T_3) and 100% inorganic (T_4) treatments, respectively (Table 2). The pattern of SOC fractions (average) extracted under a gradient of oxidizing conditions followed the trend ($C_{NL} > C_{LL} > C_{VL} > C_L$) across both nutrient and cropping systems management practices. Subsequently, the active pool and recalcitrant pool of carbon accounted for 23.5–11.1% and 76.6–77.8% of the TOC in soil under 100% organic amendment or in combination with inorganic nutrient sources across the cropping systems, respectively (Table 2).

3.5 Mineral N (NH_4^+ -N and NO_3^- -N) and Non-Labile N Fractions

After seventeen years of experimentation, nutrient management and diversified cropping has significant influence on the mineral and non-labile nitrogen fractions (Table 3). Application of 100% nutrients through inorganic sources (T_4) in CS_1 resulted in an increase of 0.7.83% and 4.26% in NH_4^+ -N compared to the 100% organic (T_1) and INM (T_3) treatments, respectively. In relation to nitrate N, observation reveals that the application of application of nitrogen through 100% inorganic sources resulted in significantly higher nitrate N as compared to organic amendments applied treatments i.e. T_1 , T_2 and T_3 across all cropping systems (Table 3). After the application of 100% inorganic nutrients (T_4) for long-term a 10.6% and 4.8% higher NO_3^- N content was detected in concomitance to 100% organic (T_1) and INM (T_3) soils, respectively. There was no discernible impact on

non-labile N content from either nutrient treatments or cropping systems. Overall, the non-labile nitrogen ranged from 0.481 to 0.443 mg kg^{-1} and 0.482–0.432 mg kg^{-1} for all treatments in CS_1 and CS_2 , respectively (Table 3).

3.6 Permanganate Oxidizable C (PmOC) and Potential Mineralizable N (PMN)

The diverse nutrient management has discernible PmOC content pattern in relation to the treatments applied in both cropping systems (Table 4). The results indicate that soils treated with 100% organic (T_1), 75% organic (T_2), and INM (T_3) yielded 35.2%, 23.1%, and 11.0% more PmOC, respectively, compared to the 100% inorganic treatment (T_4). Alternatively, the utilization of 25% and 50% inorganic fertilizers in conjunction with organic amendments resulted in a 9.8% and 18.7% decrease in PmOC in comparison to plots treated solely with 100% organic materials (Table 4). The utilization of organic amendments, (FYM and vermicompost), exhibited a noteworthy impact on the PMN content across all treatments. Treatment T_4 with sole application of synthetic fertilizers recorded 16.1%, 12%, and 16.1% lower PMN than those observed in the 100% organic (T_1), 75% organic (T_2), and INM treatments (T_3), respectively. When comparing the PMN between the cropping systems, we found a non-significant change in PMN among the cropping systems.

3.7 Microbial Biomass C (MBC) and Microbial Biomass N (MBN)

Table 4 depicts the effect of diverse nutrient management and diversified cropping sequences on soil microbial biomass carbon and nitrogen. The MBC and MBN of various nutrient treatments differed considerably according the cropping sequences (Table 4). MBC and MBN were significantly higher under 100% organic treatments (T_1) compared to other nutrient treatments ($p < 0.05$; Table 4). Soils under 100% organic treatments of both the cropping systems exhibited 48.9% and 10.9% more MBC and MBN, respectively than soils under 100% inorganic nutrient treatments. Similarly, CS_2 showed 2.8 and 3.8% higher MBC and MBN than that of CS_1 (Table 4). In general, application of organic amendments with or without inorganic sources had higher MBC and MBN in both the cropping systems.

3.8 Carbon and N Management Indexes (CMI and NMI)

The indices based on carbon and nitrogen like CMI and NMI can describe and find the changes in nutrient dynamics due to nutrient management and diversified cropping

sequences. On an average, results of C and N computation indices showed that CMI and NMI were significantly different among the nutrient management regimes and cropping systems (Supp. Figure 1). The computation of CMI and NMI suggested that they were in the range of 160.0 to 113.7, and 272.6–118.1, respectively. Application of nutrient through 100% organic amendments (T_1) under both the cropping systems registered highest CMI and NMI over the other nutrient management practices. However, CMI and NMI were 3.4% and 14.7% higher in CS_2 compared to CS_1 , respectively (Supp. Figure 1).

3.9 Mineralization of C and N (C_{min} and N_{min})

Based on the statistical analysis, a curvilinear pattern was observed for C and N mineralization during the incubation period. Compared with that in 100% inorganic nutrient treatments (T_4), soil cumulative C and N mineralization in 100% organic (T_1), 75% organic (T_2) and INM (T_3) was higher than that in T_4 ($p < 0.05$) (Supp. Figures 2 & 3). During the incubation, the cumulative C mineralization was in the following order: T_1 (14.3%) $>$ T_2 (8.0%) $>$ T_3 (11.4%) than T_4 under both the cropping systems (Supp. Figure 2). Among the cropping systems, 14.4% higher C_{min} was recorded under CS_2 than the CS_1 . In general, the N mineralization with time followed the same pattern as C_{min} (Supp. Figure 3). During the incubation period (90 days), 5.7–10.3% higher N mineralization rate was observed in soils treated with organic amendments either alone (T_1) or in combination with inorganic nutrient sources (T_2 and T_3), in comparison to 100% inorganic (T_4) treatment. However, soils under CS_1 increased N_{min} by 7.7% as compared to CS_2 .

3.10 Soil C and N Sequestration

The treatments comprised of organic and inorganic amendments either alone or in combination had significantly higher C and N sequestration compared with 100% inorganic nutrient treatment (Fig. 4). Soil C and N sequestration in both the cropping systems varied from 14.32 to 11.44 Mg C ha^{-1} , and 0.48 to 0.16 Mg N ha^{-1} , respectively. Long-term addition of 100% organic nutrients through FYM and VC (T_1) significantly enhanced the C and N sequestration over the other nutrient management regimes, and the trend was 100% organic (T_1) $>$ 75% organic (T_2) $>$ INM (T_3) $>$ 100% inorganic (T_4). Consequently, 19.2% higher N sequestration was observed in CS_2 as compared to CS_1 .

3.11 C and N Mineralization Kinetics in Soil

The mineralization pattern follows the best-fit attributes for the double-exponential first order kinetics model (Table 5).

The R^2 values mentioned denotes that the model illustrated the recorded data well. The C and N mineralization rate constant was calculated. Regardless the cropping systems, values of potential C and N mineralization (C_0 and N_0) were significantly higher ($p < 0.05$) in the soils under the organic nutrient regimes compared to 100% inorganic nutrient treatment (Table 5). Higher C_{min} and N_{min} with the lowest value of K_C and K_N values were observed in 100% organic (T_1) and 75% organic treatments (T_2) over integrated (T_3) and inorganic nutrient management (T_4) practices. The higher K_C and K_N were recorded in CS_2 as compared to CS_1 among the cropping systems. Soil with a higher half-life of C (52.9 and 34.1 days for CS_1 and CS_2 , respectively) and N (34.9 and 27.5 days for CS_1 and CS_2 , respectively) was recorded under organic management treatments. The mineralization rate constant and half-life of C and N were inversely related to each other in both the cropping systems.

3.12 Relationship between Different Pools of C and N in the Soil

The correlation matrix (r) worked out among various C and N pools in different nutrient regime soils under both the cropping systems was recorded (Supp. Figure 4). TOC content had a significant and positive correlation with CMI ($r = +0.99$; $p \leq 0.001$) (Supp. Figure 4). The (Nitrogen management index) NMI was also significantly correlated with the (Carbon management index) CMI ($r = +0.98$; $p \leq 0.001$). The SOC, PmOC, MBC, CMI, and C sequestration were significantly correlated with TON, non-labile nitrogen, PMN, MBN, NMI, and nitrogen sequestration at the same time across the cropping systems (Supp. Figure 4). The NO_3^- N and NH_4^+ N concurrently showed a significant negative correlation with all the pools of carbon. The MBN was found positively correlated with the MBC. Irrespective of cropping systems, CMI and C sequestration were significantly correlated with NMI and N sequestration. All the nitrogen pools, except NH_4^+ -N and NO_3^- N, had a significant and positive correlation with different pools of carbon in the present study. There was a significant relationship in soil C and N mineralization data of both CS_1 and CS_2 .

The regression results revealed that mineralizable nitrogen data was a significant factor (Table 6) for C-mineralization and explained 90.4% of the total variance of C and N mineralization data in CS_1 and 93.7% in the case of CS_2 . At 1% level of significance, linear regression revealed a positive relationship between C and N mineralization. The regression equation showed that per unit increase of mineralizable nitrogen in the soil, mineralized 0.63 and 0.71 units of carbon of the applied agricultural input in the soil of CS_1 and CS_2 , respectively (Table 6).

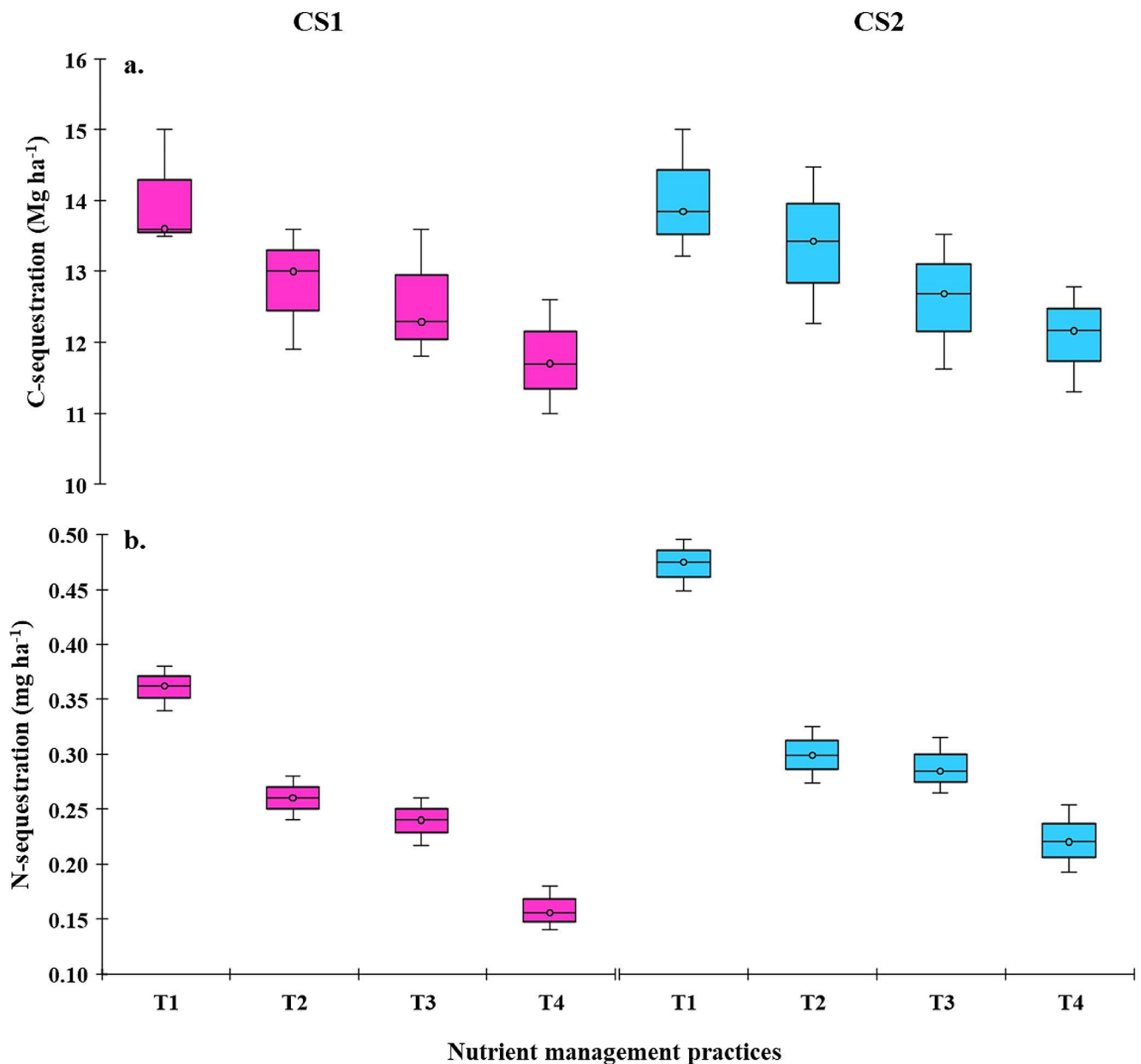


Fig. 4 C and N sequestration as influenced by long-term nutrient management options and diversified cropping under semi-arid conditions. Where T₁:100% organic, T₂:75% organic+25% inorganic, T₃: 50%

organic+50% inorganic, T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-sesbania, CS₂: Rice-barley-green gram

4 Discussion

The soils in agriculture is considered as a vital living ecosystem because of its capacity to support the plant, human and animal life. Soil health refers to the capacity of soil to deliver ecosystem services by fostering the well-being of plants, animals, and humans, and biological productivity (Vanlauwe et al. 2010). Different agricultural management practices have direct implications on functioning of ecosystem through regulation of nutrient and water flows, soil biodiversity etc. fundamental both at local and global

scale. Thus, identifying the effective management practices that counteract soil degradation and preserve the soil quality to constant supply of eco-system services is of paramount importance (Nunes et al. 2020). Adoption of conventional practices in agriculture i.e. use of organic manures and crop rotation could lead towards the sustainability goal “Land Degradation Neutrality” through combating the land degradation. SOC is considered as the foundation and store of nutrients, and thus considered a key indicator of soil fertility (Babu et al. 2023). Consequently, the present study focuses on the long-term diverse nutrient management and

Table 5 Carbon mineralization rate constant, Nitrogen mineralization rate constant, half-life of soil carbon ($C_{1/2}$), half-life of soil nitrogen ($N_{1/2}$), correlation coefficient of carbon and nitrogen mineralization as influenced by different nutrient regimes in the rice-based cropping systems

Treatments	K_C (day^{-1})		K_N (day^{-1})		R^2_C (%)		R^2_N (%)		$C_{1/2}$ (day)		$N_{1/2}$ (day)	
	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂	CS ₁	CS ₂
T ₁	0.013	0.02	0.02	0.025	86.23	89.94	73.0	77.2	52.9	34.1	34.9	27.6
T ₂	0.014	0.025	0.019	0.024	78.67	85.07	73.8	79.5	49.6	27.1	35.6	29.1
T ₃	0.020	0.038	0.032	0.037	78.09	84.63	67.5	69.2	35.5	18.0	21.6	18.6
T ₄	0.018	0.034	0.027	0.034	81.03	86.48	63.2	71.5	37.5	20.3	25.3	20.5

T₁: 100% organic; T₂: 75% organic+25% inorganic; T₃: 50% organic+50% inorganic; T₄: 100% inorganic nutrient management. CS₁: Rice-wheat-sesbania; CS₂: Rice-barley-green gram; K_C: Carbon mineralization rate constant; K_N: Nitrogen mineralization rate constant; R^2_C : Correlation coefficient of carbon; R^2_N : Correlation coefficient of nitrogen; $N_{1/2}$: Half-life of soil carbon

Table 6 The regression equations between carbon and nitrogen mineralization of soil under two rice based cropping systems

Cropping systems	Equation	R^2
Basmati rice-wheat-sesbania (CS ₁)	C= -97.45 + 155.10 N**	0.904
Coarse rice-barley-green gram (CS ₂)	C= -120.1 + 169.57 N**	0.937

diversified cropping on soil carbon sequestration and nitrogen dynamics and ultimately on ecosystem services.

The SYI evaluates the actual crop/system productivity with a long-term cultivation through application of diverse nutrient management practices (Patra et al. 2023). The results of our 7-years’ system productivity (2015–2022) showed the superiority of INM (50% organic+50% inorganic) followed by 100% organic treatment over the 100% inorganic treatment., This might be due to favourable effects of organic manures either alone or in combination of NPK resulted in higher absorption and utilization of nutrients in these treatments. Further, higher nutrient absorption helped a comprehensive development in crop growth and increased the crop yield (Meena et al. 2019). Incorporating summer green manures into the system not only contributes nutrients but also creates a conducive environment for enhanced growth and activity of soil organisms, supplementing the effects of organic manures, leading to adequate mineralization of nutrients in 100% organic, 75% organic and INM Treatments. The superior SYI under T₁, T₂ and T₃ treatments over the 100% inorganic treatment indicate increased grain production by improved nutrient accumulation to the grain which sustained crop yield in long-run in these treatments because of improved soil physico-chemical characteristics, accomplishing an advantageous soil microenvironment for root growth and enhanced nutrient absorption, resulted in higher crop production (Patra et al. 2023). The superior values of SYI as a consequence of prudent and concomitant use of organic manures either alone or with reduced doses of fertilizers ensured enhanced system/crop productivity that attributed to the cumulative effect of increase in soil physical, chemical and biological parameters, and nutrient release.

The amount and stocks of soil carbon and nitrogen are significantly influenced by the C and N inputs i.e. organic manures, green manures, crop residues, root biomass and root exudates etc. Soils enriched with organic manures either alone or as an INM practices have a greater near-equilibrium between C and N inputs, and losses through various mechanisms (Benbi et al. 2014). Thus, the superior values of TOC and TN in 100% organic treatments (T₁) in present study can be attributed to the continuous long-term application of soil organic matter through organic manures, enhancing the decomposition of added soil organic matter, and subsequent humification through a polymerization

process. (Zhao et al. 2020). Further, narrow row spacing, dense crop canopy and residue cover in winter wheat and barley crops enhanced C and N storage. Also, due to wider C: N ratio, the wheat and barley residues decompose slowly than legumes, thus increase soil TOC and TN retention in the soil (Blanco-Canqui et al. 2017).

Note that, in the present study, the 100% organic, 75% organic and INM (50% organic + 50% inorganic) were compared with 100% inorganic based nutrient management. This nutrient management system portrays the scientific comparison of typical organic production system, towards organic production (use of 75% organic manures) with completely inorganic production system. Results indicated that growing of summer pulses along with cereals for 17 years along with organic nutrient management system significantly increased the TOC and TN.

In our study, the soils that has received organic amendments either alone (T_1) or in combination with synthetic fertilizers (T_2 and T_3) recorded the better increment of SOC and different C fractions. Hence, it is proved that on-farm and off-farm organic manures are significant contributors of organic matter contributed substantially in increasing the SOC content in these treatments (Wijanarko et al., 2017; Dutta et al. 2018; Li et al. 2020). The oxidizability of different C fractions is substantially influenced by different management practices. Oxidizable organic carbon pools play a vital role in supplying nutrients to plants and soil microorganisms, thus playing a crucial part in nutrient cycling, soil quality, and overall productivity. These fractions are more sensitive indicators of soil health under different management practices. The current study identifies the relative preponderance of SOC pools in CS_1 and CS_2 following the order: $C_{NL} > C_{LL} > C_{VL} > C_L$. Labile fractions (C_{VL} and C_L) exhibit heightened sensitivity to management-induced practices when compared to recalcitrant pools (C_{LL} and C_{NL}). Availability of higher quantity of mineralizable and hydrolysable organic matter in 100% organically treated plots resulted in higher labile C fractions (C_{VL} and C_L) in these treatments over the others. Our findings are in line with the results of many previous studies (Hazra et al. 2018; Moharana et al. 2019; Meetei et al. 2020). Active TOC pools are more easily influenced by management techniques than passive carbon pools. They have been recognized as early soil health indicators due to their quick responsiveness to environmental changes (Sahoo et al. 2019). Degradable organic manure such as farmyard manure increased labile forms of C, nutrients released quickly, and improve plant yields (Sinduja et al. 2022). Furthermore, the stability and sequestration duration of organic carbon are contingent upon its chemical composition and durability of its molecular structure against degradation. Several researchers have reported that organic amendments can effectively enhance the accumulation of

degradable C functional group, such as carbohydrates, in soil (Duan et al. 2021; Zhao et al. 2023). In contrast to labile pools, higher build-up of recalcitrant pools (C_{LL} and C_{NL}) in 100% organic and 75% organic treatments can be peculiar to the stabilization of organic C in these treatments over the INM and 100% inorganic treatments due to biochemical resistance of organic C compounds in organic manures and/or residues added in these treatments. This can be correlated to higher C sequestration in the 100% and 75% organic treatments in the present study. Our results are in accordance with Bhardwaj et al. (2019) and Moharana et al. (2019).

The mineral N (NH_4^+ and NO_3^-) content is mediated by the size, activity and composition of soil biota. On one hand, part of recalcitrant N fractions (non-labile N fractions) in organic manures/crop residues remained unavailable to the crops/microbes, resulting in higher content of stable N in the soil. On the other hand, lowered C: N ratio in INM treatment (combination of organic and synthetic fertilizers) enhanced the energy for microbial N immobilization, and further increased mineral N concentration (Mohanty et al. 2013; Parihar et al. 2018; Verma et al. 2018; Zhang et al. 2021). Other studies have also reported the enhanced mineral N, soil C sequestration in cereal-legume based cropping sequences under diverse nutrient management practices (Bhardwaj et al. 2023; Meena et al. 2019). Application of high quality organic materials (N-rich, low C: N ratio i.e. leguminous green manures) enhance the substrate use efficiency of the microorganisms and thus, encourage the physico-chemical protection of organic matter through increased aggregation and chemical bonding to soil mineral particles. This resulted in higher stable N content in 100% organically and 75% organically treated soils over the INM and 100% inorganically treated plots (Meena et al. 2020; Yao et al. 2021; Dutta et al. 2022).

The incorporation of organic material substrates stimulates the microbial population in soil which directly contribute to the labile C and N pools in soil. The diverse nutrient management and diversified cropping sequence have substantial effect on MBC, MBN, PmOC and PMN as they are highly sensitive to management practices. By employing a blend of organic nutrient sources is a viable approach to enhance nutrient accessibility in organically managed soils, as it has a significant impact on the soil microbial biomass. The increase or decrease in soil organic matter (SOM) has a crucial effect on soil microbial biomass carbon (MBC) and nitrogen (MBN). (Bhattacharya et al. 2020). The higher MBC and MBN in organically treated soils of present study can be attributed to improved soil organic matter level, increased soil biological activity and stability of extracellular soil enzymes through complex humic substances in soils (Benbi et al. 2018). Moreover, the significant increase in microbial biomass in soil can be attributed to

the substantial addition of root biomass, root exudates, and readily metabolizable carbon and nitrogen found in organic manure. (Ansari et al. 2022). This can be correlated to our findings that long-term application of organic manure promotes microbial activity in the soil and encourages microorganisms to absorb nutrients and energy sources resulting in larger soil microbial biomass (Shahid et al. 2017; Benbi et al. 2018; Bhattacharya et al. 2020). The PmOC and PMN represent the biologically active states of carbon and nitrogen in soil, encompassing carbohydrates, amino acids, soil microbial biomass and other organic compounds. The rapid reaction of potassium permanganate with nascent organic molecules or complexes presents in soil, such as polysaccharides and humic substances, makes PmOC a potentially valuable tool for assessing carbon dynamics. (Dutta et al. 2022). Microbial decomposition of added organic matter in soils releases various organic N fractions. Moreover, the mineralization process of organic nitrogen results in the release of various inorganic nitrogen pools, which includes labile nitrogen, mineral nitrogen, and potential mineralizable nitrogen (PMN). The PMN is widely used as a dependable indicator of a soil's potential nitrogen-supplying capacity. It is measured as the net flux of inorganic N from the mineralizable fraction as PMN is found to be positively linked with SOC, SON, and microbial biomass. PMN indicates the balance between microbial mediated mineralization and immobilization of added organic matter. Higher PMN levels in soils indicated the accumulation of substantial amounts of mineral N, which might be attributable to the application of organic amendments on a regular basis (Zhang et al. 2018). The impact of nitrogen mineralization is significantly influenced by both the quantity and quality of organic matter. The higher quantity of dissolved organic matter, specifically the labile organic C fraction, present in the organically treated plots, led to a boost in nitrification and N mineralization. Consequently, this resulted in higher levels of PMN in these soils. (Moharana et al. 2019).

The management indexes (CMI and NMI) are important quantitative soil parameters for determining the soil quality and responsiveness to nutrient management methods. The CMI was calculated to quantify the role of various management practices on the TOC and soil fertility as well. It compares the variations in TOC and PmOC that occur as a result of various agricultural management strategies (Benbi et al. 2018). A higher CMI indicates that soil can provide more nutrients for crop development (Wang et al. 2015) and hence it is indication of soil health and quality for the sustainable crop production system. If the CMI value is greater than 100, the management system is deemed sustainable (Sharma et al. 2020). The CMI values are strongly influenced by significant changes in the labile C pool and the substrate (residues) quality (Benbi et al. 2018). On the other

hand, the NMI is an excellent predictor of soil N availability. Under CS₁ and CS₂ conditions, the CMI and NMI, both, were considerably higher in all organic and integrated nutrition treatment plots than in inorganic nutrient management sites. Carbon and nitrogen sequestration ability of any soil is greatly influenced by the equilibrium between organic input sources followed by microbial decomposition and mineralization of these organic inputs (Sindhu et al. 2020). Management induced changes that bring positive impacts on total SOC are known as carbon accumulation, whereas accumulation of carbon in recalcitrant pools (long-lived carbon pools) is known as carbon sequestration (Ghosh et al. 2018). Organic manure application might enhance SOC stock, indicating the possibility of organic C sequestration in upland soils. Long-term organic manure treatment, alone or in combination with inorganic fertilizers, might sequester SOC uniformly (Hyvonen et al. 2008). Our study has revealed that the application of organic manure promotes the accumulation of soil SOC. The results are consistent with those of Sindhu et al. (2020), who have recorded that organic manure acts as a carbon source and is assimilated into the soil, leading to an increase in organic carbon content at both micro and macro levels. On the other hand, the rate of N sequestration in both cropping systems was much greater under the organic amended treatments than chemical fertilizer treatments and it was in line with other findings (Gong et al. 2011).

In our present study, the C mineralization was significantly higher under the organically treated plot as compared to the 100% inorganically treated plot. Initially, the C_{min} was lower under the T₁ amended plot as compared to T₂, T₃ and T₄ treatments. This trend might be related to a greater C: N ratio in the soil, as well as the immobilization of available N for microorganism survival in the soil ecology as supported by the finding of others (Yang et al. 2010; Samra et al. 2017); Bhattacharya et al. 2020) that greater C: N ratio slows mineralization and reduces CO₂ emissions (Lehmann et al. 2011). Combined organic and inorganic management practices had the greatest k value, implying the lowest N half-life (Wu et al. 2017). Organically modified soils have increased N mineralization because organic N and organic C are more readily available (Sharifi et al. 2014; Mohanty et al. 2013). Under combined application, the cumulative effects of organic and inorganic fertilizers on C mineralization reduced the half-life of C and N. Organic manure provides microbial mineralization resistance (Lehmann et al. 2011; Yang et al. 2010). When compared to T₄, T₁ treatment had a longer C half-life, indicating the potential of a long-term C sequestration plan. The use of various fertilizers, particularly manure, increased the bioavailable pool of organic C and N and stimulated microbial and enzymatic activity, resulting in a greater rate of C and N mineralization

(Yang et al. 2010; Mohanty et al. 2013; Ansari et al. 2022) in soil. In long-term experiments, nitrate and ammonium are easily available forms of N in the soil that stimulate microbial activity and result in higher mineralization of C as well as microbial decomposition of applied organic manure. The negative correlation of NH_4^+ and NO_3^- content in soil with the different pools of C may be due to the higher microbial activity for organic carbon mineralization in soil. Higher microbial activities in the soil cause higher microbial respiration by utilizing the labile pools of organic C as a source of energy for their metabolic activities resulting in the loss of organic C in the soil. In our study, different pools of C were positively correlated with the different pools of N except for NH_4^+ and NO_3^- content in soil across the cropping systems. These correlations indicate that organic manure has a beneficial effect on soil and is a determinant for the availability of N from the organic amendment. Different pools of SOC and N have a positive significant relationship, which indicates their dynamic relationship in soil. NMI and TOC, PmOC, and MBC all showed a significant and positive connection (all $P < 0.01$). Changes in organic C pools had a considerable impact on N and NMI pools in accordance with CMI (Moharana et al. 2019). The soil's content of SOC and TON exhibited a robust positive correlation, characterized by a high correlation coefficient ranging from 0.80 to 0.90 (Wibowo and Kasno 2021).

5 Conclusion

Carbon and nitrogen storage in a stable solid state, achieved through both direct and indirect fixations in the soil, can lead to C and N sequestration, potentially resulting in 0.4% annual increase in the soil carbon stock and a significant decrease in atmospheric CO_2 concentration. Continuous application of organic amendments has a substantial impact on soil sustainability and agricultural production objectives, GHG emissions, C/N management efficiency, and soil health. Long-term use of soil organic amendments with or without chemical fertilizers in rice-based cropping systems had a significant influence on system productivity, SYI, CMI, NMI, as well as soil C and N dynamics, confirming our hypothesis. The Basmati rice-wheat-Sesbania (GM) and Rice-barley-green gram cropping systems had stabilised the yield (0.79 SI) in organically amended soil. Similarly, higher C/N sequestration potential was observed in Rice-barley-green gram over rice-wheat along with *Sesbania* green manuring. 100% organically amended treatment improved the CMI, NMI, C sequestration, N sequestration over 100% inorganically amended plot. However, this study gives a break from the regular barriers and illustrates the limitations. It also brings in the dynamics to promotes a clean and

sustainable production system that could be recommended for improving soil quality, long term sustainability in rice-barley-green gram cropping systems. This experiment has a focal recommendation at the regional and national level for agricultural policy planning to achieve the sustainable development goals (SDGs).

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Data Availability Data of the present study were generated as a part of All India–Network Project on Organic Farming. All the data will be made available on request.

Declarations

Competing interests The authors of the present study declare that they have no competing interest that could have appeared to influence the research work reported in this research article.

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