



RESEARCH ARTICLE

Crop residue recycling in rice-based cropping systems for soil health restoration and climate stabilisation in humid tropics

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Abstract

Soil carbon dynamics and sequestration potential are indicators of both climate change mitigation and soil health restoration. Carbon source-sink relationships in rice-based cropping systems strongly influence nutrient availability and greenhouse gas (GHG) balance. A field experiment was conducted at Integrated Farming System Research Station, Karamana, Kerala Agricultural University, to assess carbon dynamics under 8 different rice-based cropping sequences designed for soil health improvement, family nutrition, livestock feed supply and income generation. The conventional rice-fallow-fallow system served as the control. Soil samples collected at 3 depths (0–15, 15–30 and 30–45 cm) after seasonal crop residue incorporation were analysed for total organic carbon (TOC), carbon pools (labile and non-labile), particulate organic carbon (POC), water-soluble carbon (WSC) and microbial biomass carbon (MBC). Carbon fractions consistently declined with depth (0–15 cm > 15–30 cm > 30–45 cm), reflecting reduced organic inputs and microbial activity. Among the sequences, the soil health-oriented system T₃ (rice-bush cowpea-groundnut + daincha) recorded the highest TOC (6.27 %), organic carbon (1.38 %) and MBC (326.48 mg kg⁻¹), while T₄ (rice + daincha-rice + daincha-redgram + groundnut) achieved highest WSC (84.52 mg kg⁻¹) and POC (4.11 %). The income-oriented system T₉ (rice-sweet potato-cucumber) ranked second for most carbon pools and attained the highest carbon management index (290.48). Notably, T₉ also achieved a net negative GHG balance (-11920 kg CO₂ equivalent), underscoring the role of bioresource incorporation in enhancing soil carbon sequestration, improving soil health and strengthening climate resilience.

Keywords: carbon dynamics; carbon management index; climate resilience; greenhouse gas emissions; rice-based cropping sequences; soil health

Introduction

Rice-based cropping systems form the backbone of food production in the Western Coastal Plains and are particularly important in sustaining livelihoods and land productivity in coastal and lowland regions (1). In humid tropical agroecological settings, prolonged reliance on intensive rice cultivation, residue removal and simplified rotations has gradually weakened soil organic carbon reserves, reduced nutrient recovery and increased vulnerability to greenhouse gas (GHG) emissions (2, 3). These trends have raised concerns about the long-term sustainability of rice-dominated production systems and highlighted the need to improve resource use efficiency while restoring soil health (4, 5).

Soil carbon governs key soil processes, including nutrient availability, aggregate stability and microbial activity, all of which influence crop productivity and resilience (6). Evidence from tropical rice systems indicates that continuous rice-fallow or rice-rice sequences accelerate carbon depletion and limit biological regulation of nutrient cycling (7). In contrast, cropping systems that incorporate legumes, green manures and high-biomass intercrops supply diverse organic inputs that improve nutrient capturing,

strengthen microbial functioning and enhance soil carbon retention (8). These management-driven changes also influence GHG dynamics, particularly methane (CH₄) and nitrous oxide (N₂O) emissions, making carbon management a central to climate mitigation in flooded rice ecosystems (9, 10).

Recent field-based research demonstrates that on-farm recycling of rice and cereal residues through *in situ* retention, incorporation or combined organic amendments measurably restores soil function by increasing soil organic carbon (SOC), improving aggregate stability and stimulating microbial biomass and enzymatic activity compared with residue removal or burning (11). Multi-year experiments show conservation tillage coupled with residue retention produces the largest SOC gains and better water-holding capacity in paddy profiles, supporting sustained yields under humid tropical conditions (12). Experimental studies also indicate that straw incorporation alters GHG fluxes (notably transient increases in CH₄) but that integrated approaches viz., timing of incorporation, nitrogen (N) management or co-amendments such as biochar can mitigate emissions while enhancing carbon stabilisation and nutrient availability (13).

Considering these well-documented improvements in soil carbon stabilisation, nutrient cycling efficiency, crop productivity and moderated GHG emissions achieved through bioresource recycling, the present study was undertaken to systematically evaluate how diversified rice-based cropping sequences influence resource use efficiency, soil carbon pools and net GHG balance. By integrating soil health, productivity and climate indicators, the study seeks to identify cropping strategies capable of restoring degraded soils while supporting economically viable and environmentally sound rice-based agriculture.

Materials and Methods

Study details

The study evaluated soil carbon dynamics under eight diversified rice-based cropping sequences, each designed with a distinct functional objective: soil health improvement, family nutrition, livestock fodder supply and income enhancement and compared them with two prevailing systems.

For soil health enhancement, sequences included rice-bush cowpea-groundnut + daincha (T_3) and rice + daincha-rice + daincha-redgram + groundnut (T_4). Nutrition-oriented systems comprised rice-cassava + groundnut-ragi + bush cowpea (T_5) and rice-bush cowpea-sweet potato (T_6). Livestock-focused sequences were rice-guinea grass + fodder cowpea-guinea grass (regrowth) + fodder cowpea (T_7) and rice-fodder cowpea-fodder maize + fodder cowpea (T_8). Income-driven sequences included rice-sweet potato-cucumber (T_9) and rice-okra-amaranthus (T_{10}). These were assessed against the common regional practices of rice-fallow-fallow (T_1) and rice-rice-fallow (T_2).

Crop residues were quantified and incorporated back to soil after separating economic yield, to make use of the available crop resources for soil health management

Soil analysis

Soil samples were taken from three depth layers such as 0–15 cm (D_1), 15–30 cm (D_2) and 30–45 cm (D_3) at the beginning and end of each cropping sequence. All major carbon fractions including very labile, labile, less labile and non-labile carbon, as well as particulate organic carbon (POC), microbial biomass carbon (MBC), total organic carbon (TOC) and SOC were measured. At the end of each sequence, the net GHG balance was calculated.

Total organic carbon (TOC)

Total organic carbon, representing total soil organic matter carbon (decomposed + undecomposed), was determined by loss-on-ignition in a muffle furnace (14). Total organic matter (OM) (%) was computed as:

$$\text{Total OM (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Weight of sample}} \times 100 \quad (\text{Eqn. 1})$$

Total organic carbon (%) was derived from OM using: $\text{TOC} = (\text{Total OM \%}) / 1.724$.

Soil organic carbon (SOC)

Soil organic carbon was measured by wet oxidation (15). Samples were oxidised with $K_2Cr_2O_7$ and H_2SO_4 and back-titrated with ferrous ammonium sulfate (FAS). Soil organic carbon (%) was calculated as:

$$\text{Organic carbon (\%)} = \frac{(\text{Blank} - \text{Titre}) \times \text{Normality}_{\text{FAS}} \times 0.003 \times 100}{\text{Weight of soil (g)}} \quad (\text{Eqn. 2})$$

Particulate organic carbon (POC)

10 g soil were dispersed in 150 mL 0.5 % sodium hexametaphosphate for 15 hr, washed to remove silt and clay and particulate organic matter retained on a 53 μm sieve was analysed for OC (15). Particulate organic carbon (%) was calculated per the modified titration formula.

Soil carbon pools

Fractionation followed a modified Walkley-Black protocol (16):

Very labile: Oxidisable with 12 N H_2SO_4

Labile: Difference between oxidation with 18 N and 12 N H_2SO_4

Less labile: Difference between 24 N and 18 N oxidisable carbon

Non-labile: Total organic carbon (dry combustion) minus carbon oxidisable by 24 NH_4SO_4

Microbial biomass carbon (MBC)

Microbial biomass carbon was estimated by chloroform-fumigation incubation (14):

$$\text{MBC } (\mu\text{g g}^{-1}) = \frac{\text{FC} - \text{UFC}}{\text{kc}} \quad (\text{Eqn. 3})$$

where FC = CO_2 from fumigated soil, UFC = CO_2 from control and $\text{kc} = 0.45$.

Computed indices

The indices were calculated using the formulas (17).

$$\text{Carbon pool index (CPI)} = \frac{\text{Total } C_{\text{reference}}}{\text{Total } C_{\text{control}}} \quad (\text{Eqn. 4})$$

$$\text{Carbon lability index (CLI)} = \frac{\text{Lability}_{\text{reference}}}{\text{Lability}_{\text{control}}} \quad (\text{Eqn. 5})$$

Where, lability = (labile C fractions) / (non-labile C fractions).

Carbon management index (CMI) = $\text{CPI} \times \text{CLI} \times 100$ (Eqn. 6)

Greenhouse gas emissions

Net GHG emissions ($\text{CO}_2\text{-eq}$) were estimated based on life cycle approach (18). Emissions from each treatment were estimated using a standard activity-based approach, integrating activity data and corresponding emission factors (EFs) as prescribed by the Intergovernmental Panel on Climate Change (IPCC) guidelines. Activity data represented the quantities of emission-generating inputs applied, including nitrogenous fertilisers, organic manures and other relevant amendments.

Total emissions were computed using the following relationship:

$$\text{Emission} = A \times \text{EF}$$

where, emissions are expressed as tonnes of CO_2 equivalent ($\text{t CO}_2\text{-e}$), A denotes the activity data, EF represents the IPCC-recommended emission factor.

All GHG emissions were converted and reported on CO_2 -equivalent basis to ensure comparability across sources. Net emissions were derived by subtracting the carbon offsets achieved through manure incorporation and biomass production from the total emissions of the integrated farming system (IFS), thereby providing an estimate of the overall emission balance of each treatment.

Results and Discussion

Residue inputs differed markedly across systems and seasons. After the harvest of kharif rice the main-crop residues were greatest in T₄ (rice + daincha-rice + daincha-redgram + groundnut), followed by T₁₀ (rice-okra-amaranthus), T₃ (rice-bush cowpea-groundnut + daincha) and T₉ (rice-sweet potato-cucumber) with comparable contribution, whereas T₁ (rice-fallow-fallow) was lowest (Table 1). Intercrop residues occurred only in T₄, during kharif, while in major residue contributions were recorded in T₃, T₁₀ and T₆, with less residues from predominant and fodder-based sequences: T₁, T₇ and T₈. Intercrop residues were added in T₄ and T₅ (rice-cassava + groundnut-ragi + bush cowpea). In summer, main-crop residues peaked in T₃, T₄, T₅ and T₆ where bush cowpea and sweet potato have included, along with intercrop biomass residues of daincha and groundnut.

Data showed that carbon concentrations drop sharply with depth: TOC, OC and POC were highest at 0–15 cm, lower at 15–30 cm and lowest at 30–45 cm (Table 2). Microbial biomass carbon (MBC) and labile pools (very labile + labile) also declined with depth, reflecting more active organic turnover near the surface. Such surface-enrichment of active carbon pools is well-documented: surface soils tend to hold greater labile and particulate carbon than subsoil layers (19, 20). The non-labile carbon fraction remains comparatively stable through the profile, consistent with its role as the longer-term, more protected carbon reservoir. (21). Soil organic carbon (SOC) fractions, including POC and MBC, decline with increasing depth and that labile carbon pools respond more rapidly to management or vegetation changes than recalcitrant carbon pools (22, 23).

The interaction between soil depth and cropping systems, reveals a pronounced decline in MBC and POC from surface (D₁) to deeper layers (D₃) (Fig. 1). Treatments such as T₃: rice-bush cowpea-groundnut + daincha followed by T₄: rice + daincha-rice + daincha-redgram + groundnut on par shown the highest MBC and POC, reflecting greater organic matter return and enhanced microbial activity (24, 25). In contrast, lower values in T₁: rice-fallow and T₂: rice-rice indicate limited carbon inputs and weak biological functioning (26). Overall, the depth vs treatment interaction highlights that

diversified, legume-integrated systems strengthen both labile and particulate carbon pools, supporting improved soil health and long-term productivity.

Soil carbon fractionation helps to understand both the short-term turnover of organic matter and the long-term stabilisation of carbon under different cropping systems and soil depths (27). Across treatments, carbon pools showed clear depth-wise stratification (D₁ > D₂ > D₃), with higher values in surface soil (Fig. 2). Very labile and labile carbon pools were predominantly concentrated in surface soil layers and showed marked enrichment under diversified, residue-intensive cropping systems that included pulses, green manures, cereals, vegetables and tuber crops such as T₃, T₄ and T₉. These fractions declined sharply with depth due to their rapid decomposition and dependence on recent organic inputs (28–30). In contrast, less labile and non-labile carbon fractions were more stable and showed a slower decline with depth, indicating greater persistence (31). The accumulation of labile carbon on surface soil is linked to regular residue addition, enhanced rhizodeposition and increased microbial activity in diversified systems, especially those involving legumes and tuber or vegetable crops (32, 33). The relative stability of non-labile carbon reflects its association with soil aggregates and minerals, particularly in clay-rich tropical soils. Systems such as rice-sweet potato-cucumber effectively supported both rapid carbon cycling and long-term carbon stabilisation.

Carbon indices revealed that diversified treatments (T₃–T₁₀) significantly outperform conventional systems (T₁ and T₂) in enhancing soil carbon dynamics (Fig. 3). Treatments T₅, T₆ and T₉ shown elevated carbon management index (CMI) values (> 140), indicating superior carbon restoration and management. This is supported by higher carbon pool index (CPI) and carbon lability index (CLI), reflecting both quantity and quality of organic carbon. Such improvements stem from diversified crop rotations and organic inputs that stimulate microbial activity and stabilise carbon in mineral-associated forms (34, 35). The sharp contrast with T₁ and T₂ underscores the inefficacy of rice-fallow systems in sustaining soil health. These findings align with studies from tropical India and the Western Himalayas, which link crop diversity to enhanced carbon sequestration and soil resilience (36, 37).

Table 1. Season wise incorporation of crop residues into soil (kg ha⁻¹)

Cropping system	Kharif		Rabi		Summer	
	Main crop	Intercrop	Main crop	Intercrop	Main crop	Intercrop
T ₁	1942.01	0	0	0	0	0
T ₂	2195.58	0	2426.25	0	0	0
T ₃	2472.29	0	3610.48	0	1647.26	2554.34
T ₄	2511.37	2564.34	2494.82	2426.34	3839.267	1418.30
T ₅	2185.27	0	1827.05	1623.80	3747.733	3630.05
T ₆	2196.71	0	3534.24	0	2032.667	0
T ₇	2236.82	0	0	0	0	0
T ₈	2253.09	0	0	0	0	0
T ₉	2421.65	0	2034.30	0	1420	0
T ₁₀	2488.85	0	3608.65	0	0	0

Table 2. Initial soil carbon fractions at 0–15, 15–30 and 30–45 cm depths

Attributes	Total organic carbon (%)	Organic carbon (%)	Particulate organic carbon (%)	Microbial biomass carbon*	Very labile carbon*	Labile carbon*	Less labile carbon*	Non labile carbon*
D ₁ - 15 cm	4.147	1.317	2.38	175.567	1885.333	1593.333	720.000	1287.333
D ₂ - 30 cm	4.190	1.157	1.86	169.420	1374.333	1316.667	586.667	992.333
D ₃ - 45 cm	1.723	0.970	1.250	108.940	936.667	896.667	314.333	569.667
SE (m)	0.126	0.044	0.051	2.235	72.249	23.766	6.303	24.251
CD (0.05)	0.496	0.171	0.202	8.774	283.685	93.316	24.747	95.22

“*” represents the unit - mg kg⁻¹.

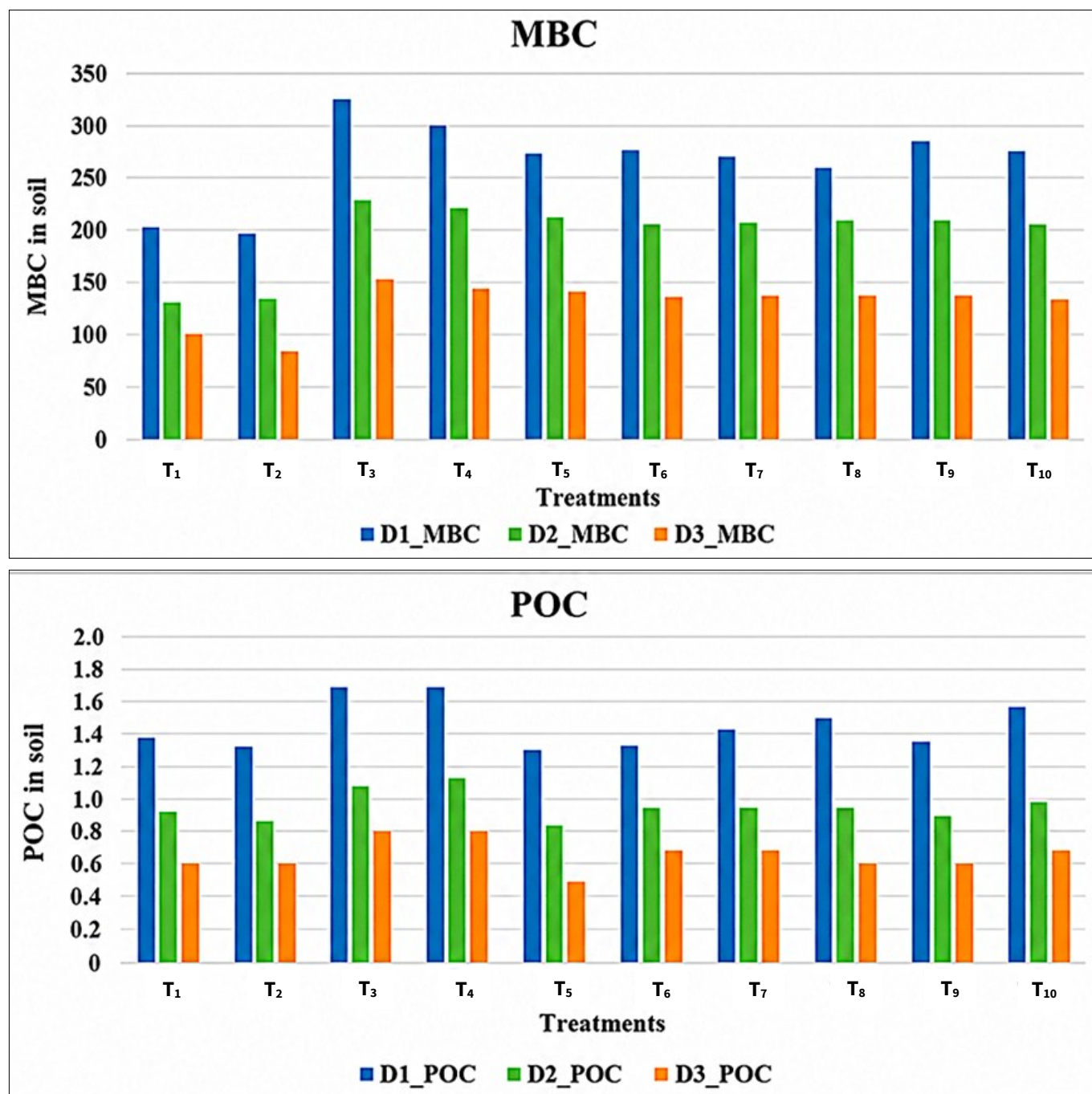
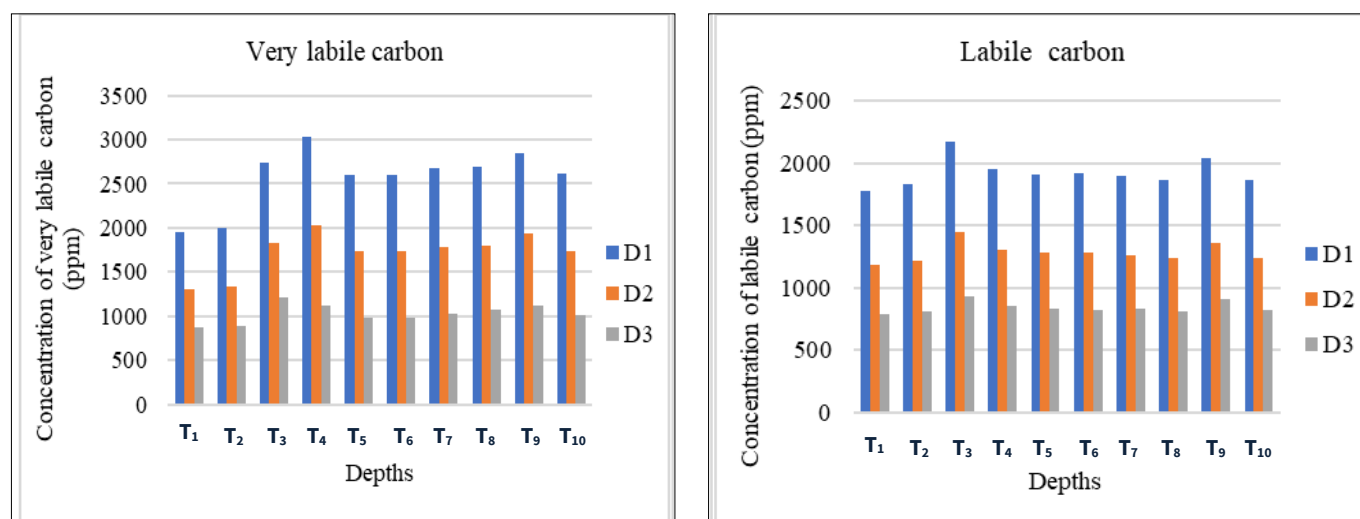


Fig. 1. Soil depth interaction of microbial biomass carbon (MBC) and particulate organic carbon (POC) in rice-based cropping systems.



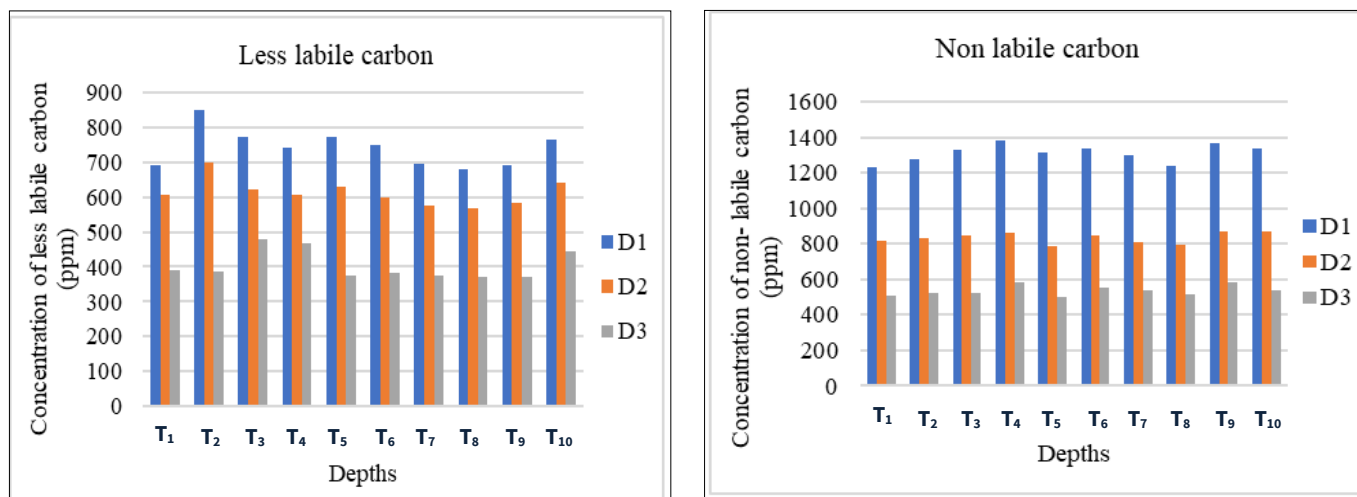


Fig. 2. Influence of carbon pools under different cropping systems.

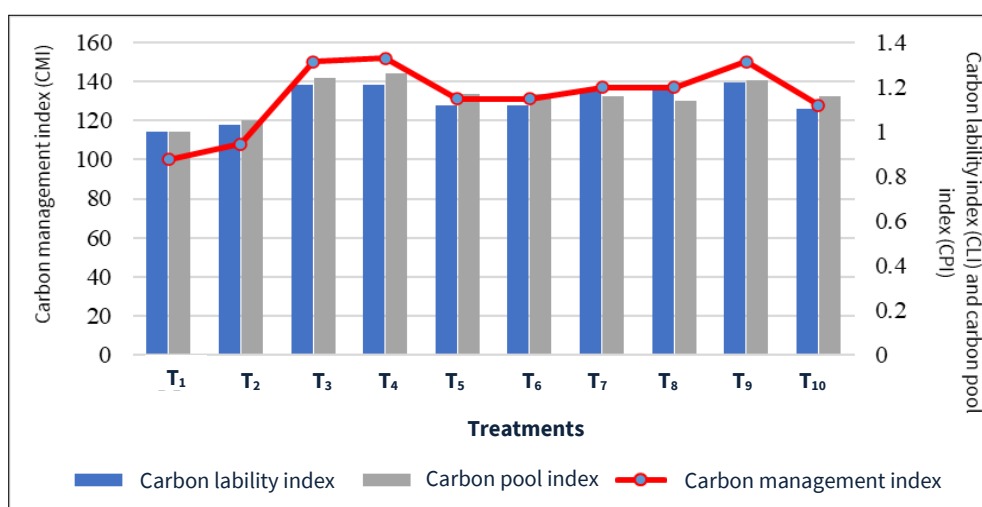


Fig. 3. Carbon indices (carbon liability index (CLI), carbon pool index (CPI) and carbon management index (CMI)) under different cropping systems.

The evaluation of cropping sequences highlights the critical role of diversification in enhancing soil carbon sequestration and reducing net GHG emissions. Conventional rice-fallow systems exhibited poor carbon retention (Fig. 4), consistent with findings that monoculture accelerates SOC depletion and increase emissions (38). In contrast, soil health-focused rotations such as rice-bush cowpea-groundnut + daincha and rice + daincha-rice + daincha-redgram + groundnut demonstrated improved sequestration, as the diversified crop rotation with residual incorporation enhances carbon stabilisation in soil aggregates (39).

Livestock-focused sequences (T₇ and T₈) contributed fodder security but showed limited sink potential, which signifies that energy-intensive fodder systems in uplands had weaker carbon budgets compared to legume-based rotations (40). Income-driven systems (T₉ and T₁₀) emerged as strong carbon sinks, which delineates that diversified rotations with legumes and tubers reduce net GHG emissions while sustaining yields (41). Plant diversity and high biomass enhance mineral-associated organic matter formation, leading for long-term sequestration (42). These results reinforce the multifunctionality of reactive minerals in stabilising soil organic carbon (43).

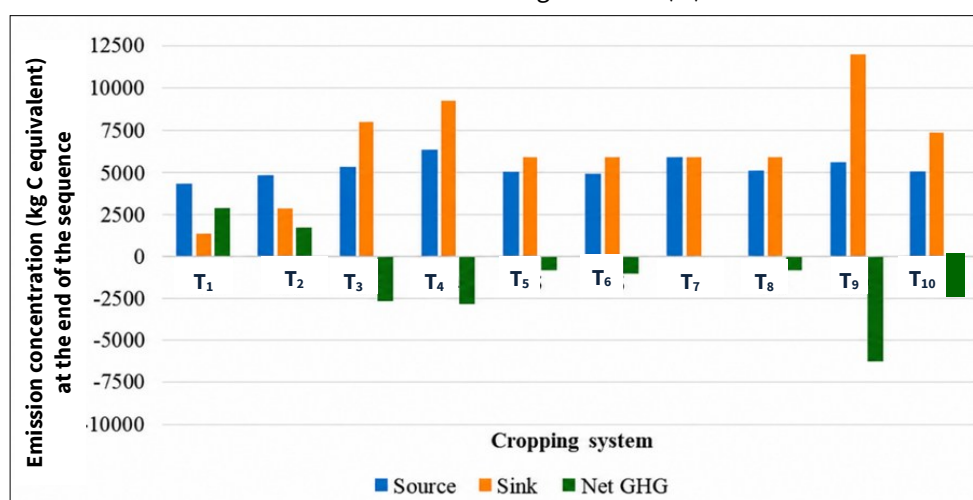


Fig. 4. Net greenhouse gas (GHG) balances across various cropping systems.

Conclusion

Diversified rice-based cropping systems improved soil carbon status by increasing both active carbon pools that support nutrient cycling and stable carbon fractions that contribute to long-term sequestration. Cropping sequences viz., rice-bush cowpea-groundnut + daincha and rice + daincha-rice + daincha-redgram + groundnut that included legumes and green manures showed higher microbial activity, better carbon management indices and lower net greenhouse gas (GHG) emissions than rice-fallow systems. These findings indicated that functional crop diversity and the biochemical quality of incorporated residues exerted a stronger control on soil carbon use efficiency than residue quantity alone, by regulating microbial processing and carbon stabilisation. Income-oriented diversified cropping system rice-sweet potato-cucumber exhibited comparable improvements in carbon sequestration and GHG mitigation, demonstrating that enhanced productivity can be achieved without compromising climate benefits. The evidence clearly indicated that systematic residue incorporation within diversified rice-based rotations played a decisive role in rebuilding soil carbon stocks, enhancing soil biological functioning and contributing to climate stabilisation in humid tropical agroecosystems.

Future research should emphasise long-term evaluation of these rice-based systems to validate their sustained carbon sequestration potential and GHG mitigation benefits under changing climatic conditions. Detailed investigations into microbial functional dynamics, carbon stabilisation mechanisms and nutrient interactions are warranted. Multi-location trials combined with economic and life-cycle assessments will further strengthen climate-smart recommendations and support the integration of carbon-efficient cropping systems into sustainable agricultural policy frameworks.

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Authors' contributions

All authors contributed to the conception, design and development of the study. RAK, MAV and RB conceptualised the study. Methodology was developed by RAK, MAV, LN and JJ. Field investigations were conducted by RAK, MAV and BJS. Data curation and formal analysis were performed by RAK, BJS and LN. Resources and supervision were provided by RB, JJ and MAV with project administration by JJ and MAV. Validation and visualisation were carried out by MAV, RB, BJS, RAK and LN. RAK drafted the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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