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Effect of adaptive management practices on carbon footprint of sugarcane in the agroecological landscape of Bihar, India

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This study evaluates adaptive management in sugarcane cultivation through varied input strategies and legume integration. A total of 380 soil samples were collected across blocks at two depths (0–15 and 15–30 cm). Results showed that at 0–15 cm, oxidizable soil organic carbon (SOC) ranged from 3.19 to 8.01 g kg⁻¹, and at 15–30 cm, it ranged from 2.50 to 6.90 g kg⁻¹. The C indices showed a decreasing trend with depth. Total organic carbon (TOC) varied from 5.68 to 11.4 g kg⁻¹ at 0–15 cm and from 3.85 to 11.4 g kg⁻¹ at 15–30 cm. Permanganate-oxidizable carbon (KMnO₄-C) ranged from 145 to 382 mg kg⁻¹ at 0–15 cm and from 122 to 356 mg kg⁻¹ at 15–30 cm. Carbon stock ranged from 12.6 to 25.9 Mg ha⁻¹ at 0–15 cm, and from 10.2 to 24.5 Mg ha⁻¹ at 15–30 cm. The active carbon pool decreased by 17.59%, the passive pool changed negligibly (0.22%) with depth; lability and recalcitrance indices showed carbon stability differences. Study offers key farm-level insights on carbon footprints and adaptive sugarcane management.

KEYWORDS

sugarcane cultivation, agricultural sustainability, soil management, carbon sequestration, climate change

1 Introduction

Agricultural agroecological landscapes cover 37% of the Earth's surface and contribute significantly to greenhouse gas (GHG) emissions (IPCC, 2006). Climate change poses a major challenge to sugarcane production, particularly in regions experiencing increased consecutive dry days, higher temperatures, and reduced precipitation (IPCC, 2021). Research by the International Sugar Organization (ISO, 2022) indicates that rising (+) temperatures and CO₂ levels have varying effects on sugarcane yields. Additionally, agricultural management practices can exacerbate environmental pollution (Wakchaure et al., 2025; Yannopoulos et al., 2015). The agricultural sector contributes significantly to global greenhouse gas emissions, accounting for up to 52% of anthropogenic methane (CH₄) and 84% of nitrous oxide (N₂O) emissions (Wakchaure et al., 2025; Bonsucro, 2023). However, it also serves as a GHG sink through C-sequestration in agricultural landscapes (Lal, 2004; Hillier et al., 2009; Tubiello et al., 2014).

Global sugarcane production rose from 448 Mt. in 1961 to over 2 Bt by 2020, expanding from 8.9 to 27 Mha. The Americas and Asia account for 93% of output, with Brazil leading and India contributing 18.7% as the second-largest producer (OECD/FAO, 2019). The increasing demand for bio-ethanol, driven by its high energy balance and reduced GHG emissions, has

intensified land use globally (Wakchaure et al., 2025; Cherubin et al., 2021). This intensification raises environmental sustainability concerns, such as soil quality degradation and ecosystem service impacts (do Amaral et al., 2008; Cherubin et al., 2016). India's sugarcane production surpassed 500 million metric tons, with large shares used for sugar and ethanol, making it a top global producer and consumer (PIB, 2022).

In India, the expansion of sugarcane cultivation is becoming increasingly important to meet the rising global demand for biofuel production. However, this expansion must be supported by adaptive soil management practices to ensure agroecological stability. Achieving this goal requires regular monitoring of soil ecosystems, which is essential for maintaining a stable and sustainable environment for soil–plant interactions. Currently, sugarcane is cultivated on 5 Mha, with an average productivity of 68 tons per hectare and a sugar recovery rate of 10%.

Sugarcane cropping systems in India struggle with low technology adoption, poor ratoon management, policy gaps, and inefficient inputs. Solutions include best agronomic practices, supportive policies, balanced nutrients, better water use, farmer training, and integrated soil health indices for accurate impact assessment.

Sugarcane farming in Bihar, covering approximately 250,000 hectares, faces challenges in maintaining production stability (Kumar et al., 2023). Productivity has declined by 5.17%, from 55.17 t/ha in 2014–15 to approximately 50.0 t/ha currently. Factors such as poor germination, inadequate cultivation practices, waterlogging, poor ratoon management, substandard seed quality, insufficient irrigation, and the neglect of plant protection measures collectively contribute to low productivity in sugarcane cultivation. A significant issue is the incorrect and imbalanced use of chemical fertilizers, primarily nitrogenous ones, which adversely affect the ecosystem through nutrient loss via leaching, runoff, and volatilization, reducing nutrient use efficiency. Additionally, the lack of organic manure application depletes soil organic matter and deteriorates soil physical conditions.

The long-term stability of agricultural production systems is closely tied to soil quality and health, necessitating effective assessment and monitoring (Brejda et al., 2000; Karlen et al., 1997). Adaptive management practices significantly influence landscape sustainability (Islam and Weil, 2000; Rezapour and Samadi, 2012). Current research aims to develop multi-parametric indicators for soil productivity and environmental health (Wakchaure et al., 2025). Despite advancements, monitoring carbon footprint remains complex due to varied agricultural landscapes (Hanson et al., 2025; Ozlu et al., 2022; De la Rosa and Sobral, 2008). Most research has focused on temperate soils, with limited data on calcareous soils in semi-arid areas (Bouma, 1989; Knoepp and Swank, 1997).

Integrating soil health indices with carbon footprint analysis is crucial for addressing climate change. Practices that degrade ecosystems often increase GHG emissions, exacerbating climate change (Lal, 2004; Smith et al., 2008). Conversely, improving soil health through sustainable practices can enhance C-sequestration, mitigate GHG emissions, and promote climate resilience (Lal, 2004). Therefore, developing comprehensive soil quality indices in relation to carbon footprints and climate change is vital for sustainable agriculture (Tubiello et al., 2014).

Despite growing interest in sustainable sugarcane production, research gaps remain on how organic inputs and diverse cropping affect soil carbon and carbon footprint, especially in calcareous soils of semi-arid to sub-tropical South Asia. Most studies focus on temperate zones, with limited field data from this key region where sugarcane supports food and biofuel security. This study hypothesizes

that the integration of organic amendments and legume-based crop diversification in sugarcane systems will enhance soil carbon sequestration, improve soil carbon pool dynamics, and stabilize carbon through improved lability and recalcitrance indices. Accordingly, the objectives are (i) to assess the impact of varying organic inputs on C-dynamics, C-stock, and C-pools and (ii) to evaluate the effect of incorporating legumes into sugarcane cropping sequences on soil organic carbon (SOC) fractions, lability, and recalcitrance indices. By addressing these objectives, the study contributes to closing the knowledge gap in carbon footprint analysis under tropical farming systems and supports the global agenda of climate-resilient, low-emission agricultural practices.

2 Materials and methods

2.1 Sampling site

The study was structured as a multi-location farmers' field trial focused on different sugarcane cropping sequences (Supplementary Table 1). The research location is an important agricultural zone within the North West Alluvial Plain Zone, characterized by a semi-arid to sub-tropical climate. Agro-climatic Zone-IV (as defined by the planning commission, now NITI Ayog), known as the "Middle Gangatic Plains Region," encompasses the entire state of Bihar, including the district of Samastipur (Figure 1). The soils of Samastipur, Bihar, are primarily alluvial in nature, classified as Entisols and Inceptisols. They have a loamy to clay-loam texture, moderate fertility, and slightly acidic to neutral pH, making them well-suited for crop cultivation. The location has a sub-tropical, semi-arid climate according to the Köppen-Geiger classification, characterized by an average annual temperature of 25.2 °C and annual rainfall of 1,236 mm (Figure 2). Summers are hot, winters are cool, and there is moderate rainfall, with the driest month being November and the highest precipitation occurring in July. The sugarcane field, managed by local farmers under Magadh Sugar and Energy Ltd., Hasanpur (Bihar), India (25.710118, 86.19065), follows standard procedures: fertilization, weed control, pest management, and leaf removal.

2.2 Site details

A total of 380 individual soil samples were combined into 38 composite samples (each comprised 10 individual soil samples) collected from Hasanpur (18), Rosera (08), Warisnagar (05), Bibhutipur (04), and Khanpur (03) blocks in the agricultural landscape of Samastipur. Soil sampling was conducted at various farmers' fields within these blocks, covering two (0–15 and 15–30 cm) soil depths. Sampling sites within each field were randomly selected to ensure comprehensive coverage of soil variability (Figure 3).

2.3 Carbon pools

Oxidizable organic carbon was estimated by titration (Walkley and Black, 1934; Jackson, 1973), and its various fractions (labile and non-labile) were determined using a modified Walkley and Black method (Chan, 2001). For total organic carbon (TOC) determination,

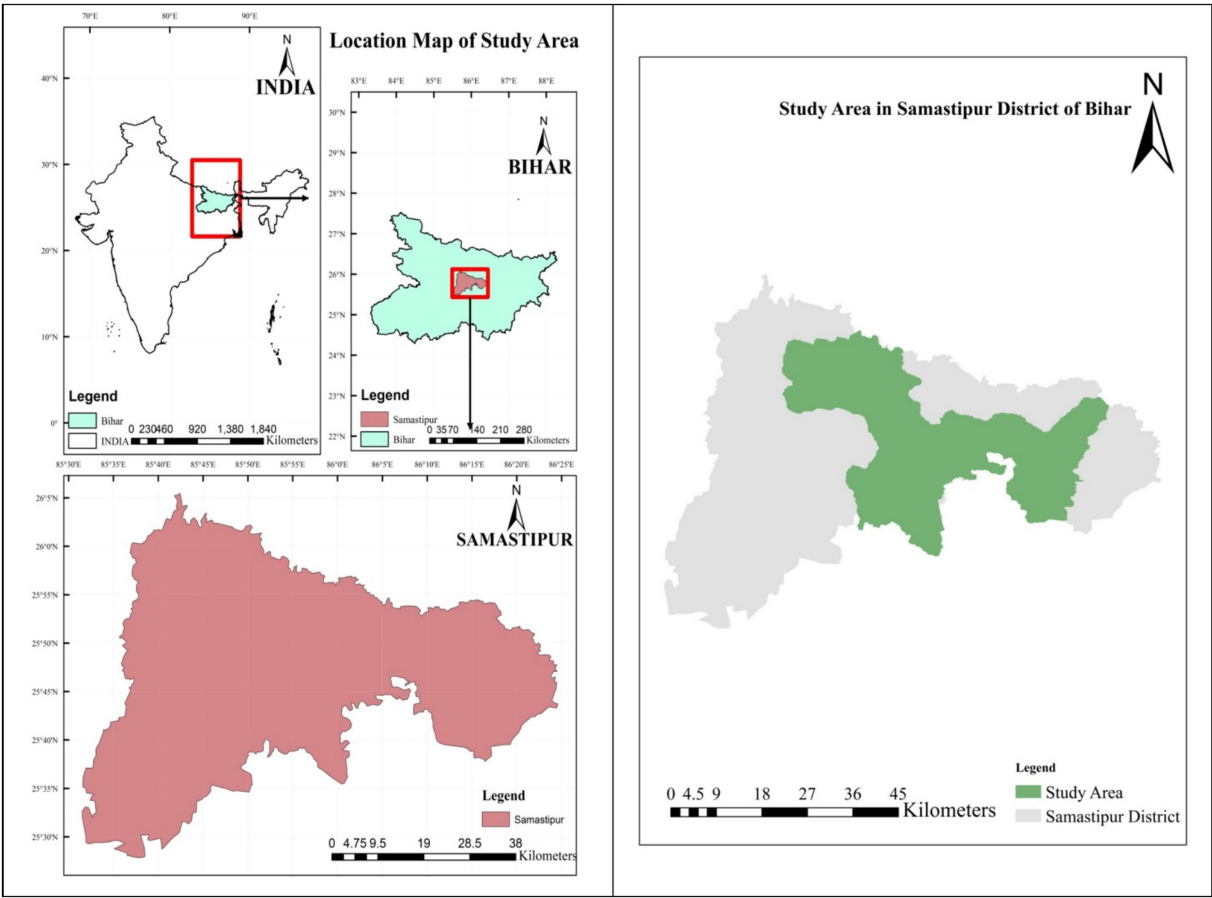


FIGURE 1
Map of the study area of Samastipur (25.7471° N, 85.8896° E), Bihar, India.

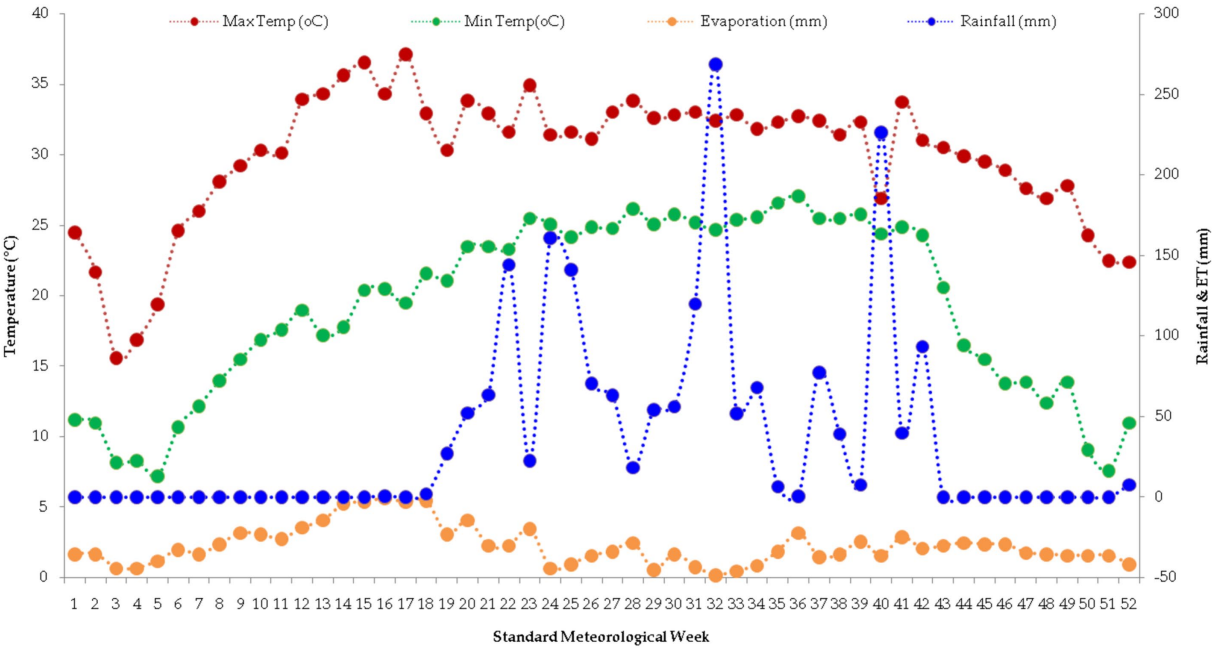
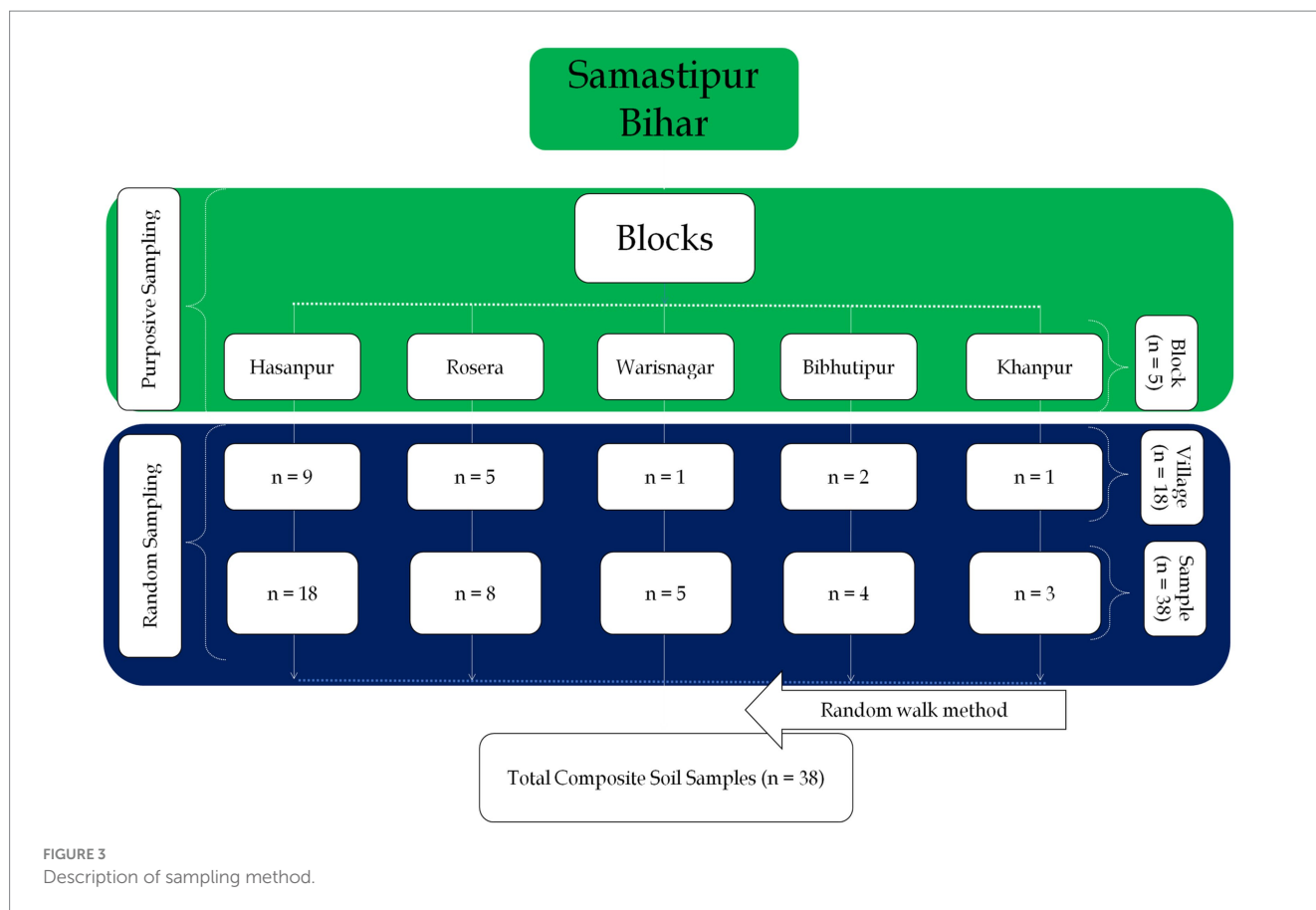


FIGURE 2
Trends in maximum and minimum temperature, evapotranspiration, and rainfall during the sugarcane growing period in Samastipur, Bihar, India.



0.25 g of the soil sample was mixed with 20 mL of 0.4 N chromic acid solution, heated at 155–160 °C for 20–25 min, and then cooled to room temperature (Jackson, 1973). Active carbon was estimated by quantifying potassium permanganate (KMnO₄) oxidation with a spectrophotometer (Weil et al., 2003). Carbon stock and its active/passive pools were estimated (Equations 1–3), while lability and recalcitrance indices were calculated as per Datta et al. (2015) (Equations 4–6).

$$\text{SOC} - \text{Stock} \left(\text{Mg ha}^{-1} \right) = \text{TOC}(\%) \times \text{BD} \left(\text{Mg m}^{-3} \right) \times D(m) \quad (1)$$

where,

SOC = soil organic carbon; TOC = total organic carbon; BD = bulk density; D = depth of soil

$$\text{CAP} = \{ \Sigma (\text{VLC} + \text{LC}) \} \quad (2)$$

where,

CAP = carbon active pool; VLC = very labile carbon; LC = labile carbon

$$\text{CPP} = \{ \Sigma (\text{LLC} + \text{NLC}) \} \quad (3)$$

where,

CPP = carbon passive pool; LLC = less labile carbon; NLC = non-labile carbon

$$\text{LI} = 3 \text{ LI} = \frac{\text{VLC}}{\text{TOC}} + 2 \frac{\text{LC}}{\text{TOC}} + \frac{\text{LLC}}{\text{TOC}} \quad (4)$$

$$\text{RI1} = \frac{\text{LLC} + \text{NLC}}{\text{LLC} + \text{LC}} \quad (5)$$

$$\text{RI2} = \frac{\text{NLC}}{\text{TOC}} \quad (6)$$

where,

LI = lability index; VLC = very labile carbon; LC = labile carbon; LLC = less labile carbon; TOC = total organic carbon; NLC = non-labile carbon; RI = recalcitrance index.

2.4 Statistical analysis

The study was structured as a multi-location farmers' field trial, where ongoing demonstrations served as replications across different sugarcane-based cropping sequences. Data were collected over cropping years in the North West Alluvial Plain Zone of Bihar. Descriptive statistics for various soil and crop parameters were generated using IBM SPSS (v26). Location maps of the study sites were prepared in ArcGIS 10.8.2. To evaluate multi-location effects, analysis of variance (ANOVA) was performed. Replication and multi-location

effects (treatment) effects across the experimentation were modeled as random factors, and variance components were estimated using Restricted Maximum Likelihood (REML). Degrees of freedom were adjusted using the Satterthwaite approximation to improve accuracy. Treatment means were compared using the critical difference (CD) test at the 5% significance level ($p \leq 0.05$), and standard errors (SE) were calculated for all comparisons. For transparency, F -values, degrees of freedom, p -values, and effect sizes (95% CI) are reported in the results.

3 Results and discussion

3.1 Oxidizable organic carbon

The data revealed significant variation in oxidizable SOC content across different soil depths within the studied agricultural landscape (Table 1). At a depth of 0–15 cm, mean SOC content was 5.23 g kg^{-1} . It ranged from 3.17 to 8.01 g kg^{-1} , and exhibited a slight positive skewness (0.30) and leptokurtic distribution (kurtosis = 0.73). In contrast, at a deeper soil depth of 15–30 cm, the mean SOC content decreased (4.56 g kg^{-1}), and it ranged from 2.50 to 6.90 g kg^{-1} , with skewness (0.19) and lower kurtosis (0.33). Overall, the SOC content decreased (12.8%) at 15–30 cm depth. SOC content decreased with increasing soil depth, indicating a clear vertical gradient in its distribution. This pattern is critical for understanding nutrient dynamics and assessing soil health in agricultural ecosystems (Table 1). Continuous addition of above-ground biomass and decaying roots significantly influences C-levels. Research by Dotaniya et al. (2014) highlighted that organic amendments enhance C-content and stimulate microbial activity. The observed slight increase in integration of organic manure (OM) and mineral fertilizer application can be attributed to improved crop growth and higher yield, leading to increased residue and root exudate inputs that decompose and enrich the SOC. Similar findings have been reported by More et al. (2007), Bokhtiar et al. (2008), Jha et al. (2017), Sinha et al. (2017a), and Mthimkhulu et al. (2016), reinforcing the positive impact of organic inputs on soil fertility and C-dynamics.

3.2 Total organic carbon

Data showed that the mean TOC content was 7.64 g kg^{-1} . It ranged from 5.68 to 11.4 g kg^{-1} , showing a positively skewed

distribution (skewness = 1.57) and slightly leptokurtic shape (kurtosis = 1.11) at 0–15 cm. Meanwhile, at 15–30 cm, the mean SOC content decreased to 7.10 g kg^{-1} and ranged from 3.85– 11.4 g kg^{-1} , exhibiting a similar positively skewed distribution (skewness = 1.38) and lower kurtosis (kurtosis = 0.74) compared to the 0–15 cm depth. A 7.1% decline in mean TOC content was observed at the 15–30 cm soil depth (Table 1). Understanding the factors influencing variations in TOC levels, such as land use practices, soil management strategies, and climatic conditions, is crucial for optimizing sustainable agricultural practices and C-sequestration. OM application to soil, as observed with SOC, plays a significant role in enhancing C-content. This phenomenon is supported by findings in the literature (Dotaniya et al., 2014; More et al., 2007; Bokhtiar et al., 2008; Jha et al., 2017; Sinha et al., 2017b; Mthimkhulu et al., 2016), which highlight the positive impact of organic inputs on C-dynamics. By elucidating these relationships, researchers can better formulate strategies to enhance SOC levels and improve soil health, thereby contributing to broader environmental sustainability goals (Table 1).

3.3 $\text{KMnO}_4\text{-C}$

Results showed that $\text{KMnO}_4\text{-C}$ content in the soil varied between depths in the agricultural landscape (Table 1). At 0–15 cm, the mean $\text{KMnO}_4\text{-C}$ content was $263.26 \text{ mg kg}^{-1}$, and it ranged from 145 to 382 mg kg^{-1} , showing a negatively skewed distribution (skewness = -0.20) and platykurtic shape (kurtosis = -0.13). While at 15–30 cm, the mean $\text{KMnO}_4\text{-C}$ content decreased to $235.69 \text{ mg kg}^{-1}$ and ranged from 122 to 356 mg kg^{-1} , displaying similar skewness (skewness = -0.19) and kurtosis (kurtosis = -0.05) compared to the 0–15 cm depth (Table 1). The variation in the soil depth was 10.5%. This observed decline in $\text{KMnO}_4\text{-C}$ levels with increasing soil depth suggests a gradient in C-availability that is pivotal for understanding SOC dynamics and nutrient cycling in agricultural systems. Further exploration of factors influencing $\text{KMnO}_4\text{-C}$, such as management practices and soil physical properties, is essential to optimize C-sequestration and enhance soil health strategies. Higher $\text{KMnO}_4\text{-C}$ in the 0–15 cm layer may be attributed to enhanced root biomass, rhizodeposition, and microbial activity. Monitoring labile organic matter fractions offers a sensitive and effective approach for evaluating soil quality dynamics (Needelman et al., 1999; Ding et al., 2006; Benbi et al., 2015; Meena et al., 2021).

TABLE 1 Descriptive statistics of oxidizable, total, and $\text{KMnO}_4\text{-C}$ of sugarcane growing area.

Descriptive statistics	Oxidizable-SOC (g kg^{-1})		Total-SOC (g kg^{-1})		$\text{KMnO}_4\text{-C}$ (mg kg^{-1})	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Mean	5.23	4.56	7.64	7.10	263.26	235.69
Standard error	0.17	0.16	0.19	0.24	9.03	8.82
Standard deviation	1.06	0.96	1.20	1.49	55.6	54.3
Sample variance	1.13	0.92	1.44	2.21	3,100	2,957
Skewness	0.30	0.19	1.57	1.38	-0.20	-0.19
Kurtosis	0.73	0.33	1.11	0.74	-0.13	-0.05
Minimum	3.17	2.50	5.68	3.85	145	122
Maximum	8.01	6.90	11.4	11.4	382	356

3.4 Very labile carbon and labile carbon

Data showed that a significant variation was found in VL-C and L-C content across different depths within the agricultural landscape (Table 2). At 0–15 cm, the mean C-VL content was 1.56 g kg^{-1} and ranged from 1.02 to 2.60 g kg^{-1} , showing a positively skewed distribution (skewness = 0.63) and platykurtic shape (kurtosis = -0.58). However, at 15–30 cm, the mean C-VL content decreased to 1.31 g kg^{-1} , and ranged from 0.90 to 1.98 g kg^{-1} , exhibiting a similar positively skewed distribution (skewness = 0.68) and slightly lower kurtosis (kurtosis = -0.31) compared to the 0–15 cm depth. The decline in mean C-VL content from 0–15 cm to 15–30 cm depth was 16% (Table 2).

Meanwhile, C-L in the soil showed variations across different depths (Table 2). At 0–15 cm, the mean C-L content was 1.50 g kg^{-1} and ranged from 1.13 to 2.08 g kg^{-1} , showing a positively skewed distribution (skewness = 0.33) and slightly platykurtic shape (kurtosis = -0.32). In contrast, at 15–30 cm, the mean C-L content decreased to 1.22 g kg^{-1} and ranged from 0.43 to 1.97 g kg^{-1} , exhibiting a similar positively skewed distribution (skewness = 0.13) and leptokurtic shape (kurtosis = 0.88) compared to the 0–15 cm depth. The decrease in mean C-L content from 0–15 cm to 15–30 cm depth was approximately 18.7% (Table 2). These higher VL-C and L-C contents signify enhanced microbial activity and OM turnover (Meena et al., 2018; Meena et al., 2021). Monitoring these fractions provides insights into the responsiveness of soil carbon pools to management practices, facilitating sustainable agricultural strategies aimed at enhancing soil health and C-sequestration efforts (Table 2). Integrated studies on sugarcane highlight that sustainable trash management (Gadge et al., 2017; Shanthi et al., 2020), conservation tillage (de Oliveira et al., 2022; Turmel et al., 2015), and optimized fertigation (Ravikumar et al., 2011) are key to enhancing productivity, improving soil health, and ensuring long-term ecological balance.

3.5 Less labile carbon and non-labile carbon

Results showed that less labile carbon (LL-C) content at 0–15 cm soil layer ranged from 0.93 – 3.33 g kg^{-1} , with a mean value (2.16 g kg^{-1}), showing a slightly positively skewed distribution (skewness = 0.14) and mesokurtic shape (kurtosis = 0.39). At

15–30 cm, the mean LL-C content slightly decreased to 2.04 g kg^{-1} and ranged from 1.00 – 3.45 g kg^{-1} , exhibiting a similar positively skewed distribution (skewness = 0.48) and higher kurtosis (kurtosis = 0.85) compared to the 0–15 cm depth. The slight decrease in mean LL-C content from 0–15 cm to 15–30 cm depth was approximately 5.6% (Table 2).

Meanwhile, in the case of NL-C at 0–15 cm, the mean was 2.41 g kg^{-1} and ranged from 1.48 to 3.41 g kg^{-1} , showing a positively skewed distribution (skewness = 0.41) and a highly leptokurtic shape (kurtosis = 4.70). At 15–30 cm, the mean NL-C content slightly increased to 2.54 g kg^{-1} , ranging from 1.35 – 4.54 g kg^{-1} , exhibiting a similar positively skewed distribution (skewness = 0.98) and lower kurtosis (kurtosis = 0.82) compared to the 0–15 cm depth. The slight increase in mean NL-C content from 0–15 cm to 15–30 cm depth was 5.4% (Table 2). Sugarcane trash, being less prone to microbial decomposition, tends to accumulate as passive SOC over time. This phenomenon underscores the role of agricultural practices in influencing C-dynamics, where annual additions of sugarcane trash to the surface layer may enhance the active C-fraction compared to the deeper layer. Crop residues support microbial proliferation, which in turn stimulates nutrient cycling and enhances soil fertility (Ensinas et al., 2015; Mir et al., 2023). Additionally, Majumder et al. (2008) support the idea that management options influence the balance between C-inputs (e.g., root biomass, litter fall) and outputs (e.g., heterotrophic respiration), thereby affecting soil carbon pools. These findings align with studies by Mir et al. (2023) and Benbi et al. (2015), which emphasize the importance of understanding carbon dynamics in agricultural systems to optimize carbon management strategies and mitigate climate change impacts (Table 3).

3.6 Carbon stock

Carbon stock in the soil varied across different depths within the agricultural landscape (Table 3). Results showed that the mean C-stock (17.00 Mg ha^{-1}) ranged from 12.6 to 25.9 Mg ha^{-1} at 0–15 cm and showed a positively skewed distribution (skewness = 1.18) and leptokurtic shape (kurtosis = 2.19). At 15–30 cm, the mean C-stock slightly decreased to 16.72 Mg ha^{-1} and ranged from 10.2 to 24.5 Mg ha^{-1} , exhibiting a similar positively skewed distribution (skewness = 0.62) and slightly lower kurtosis (kurtosis = 0.59) compared to the 0–15 cm depth. The decrease in mean C-stock from

TABLE 2 Descriptive statistics of various carbon fractions of sugarcane growing area.

Descriptive statistics	C-VL (g kg^{-1})		C-L (g kg^{-1})		C-LL (g kg^{-1})		C-NL (g kg^{-1})	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Mean	1.56	1.31	1.50	1.22	2.16	2.04	2.41	2.54
Standard error	0.07	0.04	0.04	0.05	0.09	0.08	0.05	0.11
Standard deviation	0.42	0.26	0.24	0.29	0.54	0.50	0.29	0.70
Sample variance	0.17	0.07	0.06	0.09	0.29	0.25	0.09	0.49
Skewness	0.63	0.68	0.33	0.13	0.14	0.48	0.41	0.98
Kurtosis	-0.58	-0.31	-0.32	0.88	0.39	0.85	4.70	0.82
Minimum	1.02	0.90	1.13	0.43	0.93	1.00	1.48	1.35
Maximum	2.60	1.98	2.08	1.97	3.33	3.45	3.41	4.54

TABLE 3 Descriptive statistics of C-stock and C-pools of sugarcane growing area.

Descriptive statistics	TOC stock (Mg ha ⁻¹)		Active pool (g kg ⁻¹)		Passive pool (g kg ⁻¹)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Mean	17.00	16.72	3.07	2.53	4.57	4.58
Standard error	0.44	0.48	0.10	0.09	0.11	0.18
Standard deviation	2.70	2.93	0.63	0.53	0.66	1.08
Sample variance	7.27	8.58	0.39	0.28	0.43	1.16
Skewness	1.18	0.62	0.56	0.36	1.11	1.00
Kurtosis	2.19	0.59	−0.30	−0.44	2.19	1.86
Minimum	12.6	10.2	2.15	1.43	3.44	2.42
Maximum	25.9	24.5	4.68	3.65	6.74	7.99

TABLE 4 Descriptive statistics of lability and recalcitrance index of sugarcane growing area.

Descriptive statistics	LI		RI-1		RI-2	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Mean	1.28	1.19	1.52	1.83	0.32	0.36
Standard error	0.01	0.02	0.04	0.05	0.01	0.01
Standard deviation	0.09	0.11	0.24	0.31	0.04	0.05
Sample variance	0.01	0.01	0.06	0.10	0.00	0.00
Skewness	0.08	0.22	1.27	0.18	0.14	0.21
Kurtosis	−0.88	−1.55	2.25	−0.79	0.61	−1.18
Minimum	1.10	1.04	1.23	1.33	0.22	0.28
Maximum	1.47	1.38	2.32	2.53	0.44	0.46

0–15 cm to 15–30 cm depth was 1.6% (Table 3). The decline in mean C-stock from 0–15 cm to 15–30 cm depth highlights significant variations in organic carbon storage, crucial for soil fertility, C-sequestration, and overall soil health in the region (Table 3). Recent studies by Ensinas et al. (2015) emphasize the role of cropping systems, such as sugarcane cultivation, in influencing C-stocks and GHG mitigation. Further research on TOC dynamics, soil properties, and management practices is essential for optimizing carbon management strategies in agricultural landscapes (Benbi et al., 2015; Majumder et al., 2008; Sherrod et al., 2005; Mir et al., 2023).

3.7 Active and passive carbon pools

Data showed that active and passive carbon pools varied across the soil depths (Table 3) within the agricultural landscape. At 0–15 cm, the mean active pool was 3.07 g kg⁻¹, and it ranged from 2.15 to 4.68 g kg⁻¹, showing a moderately positively skewed distribution (skewness = 0.56) and a slightly negative kurtosis (kurtosis = −0.30). At 15–30 cm, the mean active pool decreased to 2.53 g kg⁻¹, and it ranged from 1.43 to 3.65 g kg⁻¹, indicating a similar positively skewed distribution (skewness = 0.36) and a more negative kurtosis (kurtosis = −0.44) compared to the 0–15 cm depth. Overall, these findings indicated a decrease (17.59%) in the mean active pool of soil carbon from the 0–15 cm to the 15–30 cm soil depths. However, the passive pool of soil carbon showed a negligible change of approximately 0.22% from the 0–15 cm to the 15–30 cm soil depths

(Table 3). These findings underscore the complex dynamics of soil carbon storage and turnover, crucial for optimizing C-sequestration and soil fertility management strategies (Lal, 2004; Paustian et al., 2000; Regnier et al., 2022; Tubiello et al., 2021; Wieder et al., 2015; Fan et al., 2023; Chen et al., 2022; Batjes et al., 2020).

3.8 Lability and recalcitrance index

The data indicated that LI, RI-I, and RI-II values varied significantly across different soil depths (Table 4). At the 0–15 cm depth, the mean LI was 1.28 and ranged from 1.10 to 1.47. The distribution showed a slight positive skewness (skewness = 0.08) and exhibited a platykurtic shape (kurtosis = −0.88), indicating a relatively flat distribution compared to a normal distribution. At the 15–30 cm depth, the mean LI slightly decreased to 1.19 and ranged from 1.04 to 1.38, with higher positive skewness (skewness = 0.22) and more negative kurtosis (kurtosis = −1.55), suggesting a more peaked and narrower distribution compared to the 0–15 cm depth (Table 4).

Meanwhile, in the case of RI-1 at 0–15 cm depth, the mean was 1.52 and varied from 1.23 to 2.32 with positive skewness (skewness = 1.27) and exhibited leptokurtic shape (kurtosis = 2.25). At 15–30 cm depth, the mean was increased to 1.83 and ranged from 1.33 to 2.53. Distribution showed a lower positive skewness (skewness = 0.18) and negative kurtosis (kurtosis = −0.79), indicating a more flattened and broader distribution compared to the 0–15 cm depth (Table 4). Similarly, in the case of RI-2 at 0–15 cm depth, the

mean was 0.32 and ranged from 0.22 to 0.44, indicating a relatively narrow distribution. The distribution showed a slight positive skewness (skewness = 0.14) and exhibited a slightly leptokurtic shape (kurtosis = 0.61), suggesting a moderately peaked distribution compared to a normal distribution. At 15–30 cm depth, the mean RI-2 increased slightly to 0.36, and values ranged from 0.28 to 0.46, indicating a slightly wider distribution compared to the 0–15 cm depth. The distribution showed a positive skewness (skewness = 0.21) and negative kurtosis (kurtosis = −1.18), suggesting a flatter and broader distribution compared to the 0–15 cm depth (Table 4). These findings underscore the importance of understanding C-stability dynamics in soil profiles, crucial for implementing effective soil management strategies to enhance C-sequestration and mitigate climate change impacts (Hassink, 1997; Poeplau and Don, 2015; Yang et al., 2024; Nie et al., 2024; Lu et al., 2024; Adhikari et al., 2024; Meena et al., 2024).

3.9 Correlation matrix

The correlation matrix revealed significant relationships among soil parameters across different soil depths within the studied agricultural landscape (Tables 5, 6). OC refers to organic carbon in soil organic matter, while TOC is a broader term that includes all forms of organic carbon, both particulate and dissolved, providing a more comprehensive measure. At the 0–15 cm soil depth, pH was negatively correlated with TOC ($r = -0.732^{**}$) and $\text{KMnO}_4\text{-C}$ ($r = -0.710^{**}$), indicating reduced carbon levels with increasing pH. In contrast, EC showed strong positive correlations with TOC ($r = 0.750^{**}$) and $\text{KMnO}_4\text{-C}$ ($r = 0.757^{**}$). Nitrogen exhibited the highest correlation with TOC ($r = 0.903^{**}$) and $\text{KMnO}_4\text{-C}$ ($r = 0.906^{**}$). Sulfur and water-stable aggregates (WSA) were also strongly associated with $\text{KMnO}_4\text{-C}$ ($r = 0.888^{**}$ and $r = 0.806^{**}$, respectively), suggesting their key roles in carbon stabilization (Table 5). Meanwhile, at 15–30 cm depth, nitrogen

TABLE 5 Correlation matrix between soil health parameters and soil carbon pools (0–15 cm soil depth).^a

Correlation matrix	OC	VL-C	L-C	LL-C	NL-C	TOC	TOC stock	$\text{KMnO}_4\text{-C}$
PH	−0.745**	−0.615**	−0.559**	−0.747**	−0.287 ^{NS}	−0.732**	−0.628**	−0.710**
EC	0.774**	0.766**	0.692**	0.631**	0.252 ^{NS}	0.750**	0.663**	0.757**
N	0.929**	0.832**	0.755**	0.857**	0.316 ^{NS}	0.903**	0.795**	0.906**
P_2O_5	0.568**	0.516**	0.377*	0.554**	0.041 ^{NS}	0.514**	0.495**	0.641**
K_2O	0.448**	0.405*	0.305 ^{NS}	0.436**	−0.023 ^{NS}	0.392*	0.282 ^{NS}	0.513**
S	0.875**	0.795**	0.747**	0.783**	0.317 ^{NS}	0.855**	0.755**	0.888**
Zn	0.474**	0.457**	0.427**	0.392*	0.170 ^{NS}	0.462**	0.484**	0.450**
Cu	0.477**	0.508**	0.312 ^{NS}	0.411*	0.022 ^{NS}	0.429**	0.372*	0.459**
Fe	0.482**	0.480**	0.312 ^{NS}	0.442**	−0.015 ^{NS}	0.424**	0.358*	0.473**
Mn	0.506**	0.492**	0.323*	0.474**	−0.006 ^{NS}	0.448**	0.358*	0.505**
BD	−0.263 ^{NS}	−0.123 ^{NS}	−0.187 ^{NS}	−0.340*	0.118 ^{NS}	−0.204 ^{NS}	0.210 ^{NS}	−0.276 ^{NS}
WSA	0.787**	0.781**	0.764**	0.612**	0.306 ^{NS}	0.774**	0.690**	0.806**

^aPH, Potential of Hydrogen; EC, Electrical Conductivity; N, Nitrogen; P_2O_5 , Available Phosphorus; K_2O , Available Potassium; S, Sulfur; Zn, Zinc; Cu, Copper; Fe, Iron; Mn, Manganese; BD, Bulk Density; WSA, Water-Stable Aggregates; OC, Organic Carbon; VL-C, Very Labile Carbon; L-C, Labile Carbon; LL-C, Less Labile Carbon; NL-C, Non-Labile Carbon; TOC, Total Organic Carbon; TOC Stock, Total Organic Carbon Stock; $\text{KMnO}_4\text{-C}$, Permanganate-Oxidizable Carbon.

TABLE 6 Correlation matrix between soil health parameters and soil carbon pools (15–30 cm soil depth).

Correlation matrix	OC	VL-C	L-C	LL-C	NL-C	TOC	TOC stock	$\text{KMnO}_4\text{-C}$
PH	−0.586**	−0.489**	−0.508**	−0.566**	−0.243 ^{NS}	−0.493**	−0.417**	−0.286 ^{NS}
EC	−0.270 ^{NS}	−0.361*	−0.215 ^{NS}	−0.199 ^{NS}	−0.010 ^{NS}	−0.179 ^{NS}	−0.071 ^{NS}	0.068 ^{NS}
N	0.863**	0.764**	0.801**	0.778**	0.569**	0.826**	0.814**	−0.109 ^{NS}
P_2O_5	0.709**	0.568**	0.661**	0.669**	0.545**	0.715**	0.647**	0.082 ^{NS}
K_2O	0.512**	0.442**	0.470**	0.471**	0.215 ^{NS}	0.432**	0.411*	0.132 ^{NS}
S	0.792**	0.655**	0.755**	0.728**	0.493**	0.744**	0.699**	0.166 ^{NS}
Zn	0.479**	0.484**	0.360*	0.450**	0.191 ^{NS}	0.399*	0.276 ^{NS}	0.074 ^{NS}
Cu	0.478**	0.488**	0.350*	0.450**	0.210 ^{NS}	0.407*	0.286 ^{NS}	0.070 ^{NS}
Fe	0.540**	0.548**	0.419**	0.498**	0.227 ^{NS}	0.455**	0.333*	0.103 ^{NS}
Mn	0.575**	0.549**	0.465**	0.537**	0.259 ^{NS}	0.493**	0.375*	0.119 ^{NS}
BD	−0.763**	−0.600**	−0.688**	−0.740**	−0.512**	−0.734**	−0.620**	−0.152 ^{NS}
WSA	0.708**	0.568**	0.631**	0.683**	0.519**	0.701**	0.578**	0.139 ^{NS}

showed strong positive correlations with TOC ($r = 0.826^{**}$) and OC ($r = 0.863^{**}$). Sulfur and phosphorus were also highly correlated with TOC ($r = 0.744^{**}$ and $r = 0.715^{**}$, respectively). In contrast, bulk density was strongly negatively correlated with TOC ($r = -0.734^{**}$) and OC ($r = -0.763^{**}$). Unlike in the surface layer, $\text{KMnO}_4\text{-C}$ showed no significant associations, indicating its lower sensitivity at this depth (Tables 5, 6). Recent studies underscore the importance of sustainable sugarcane cultivation using efficient irrigation (Gunarathna et al., 2018), trash and tillage practices (Surendran et al., 2016; Solomon, 2016; Suma and Savitha, 2015), and precision nutrient management (Basanta et al., 2003; Choudhary et al., 2017). These strategies improve yield, enhance soil health, and boost resource use efficiency (Powar et al., 2021).

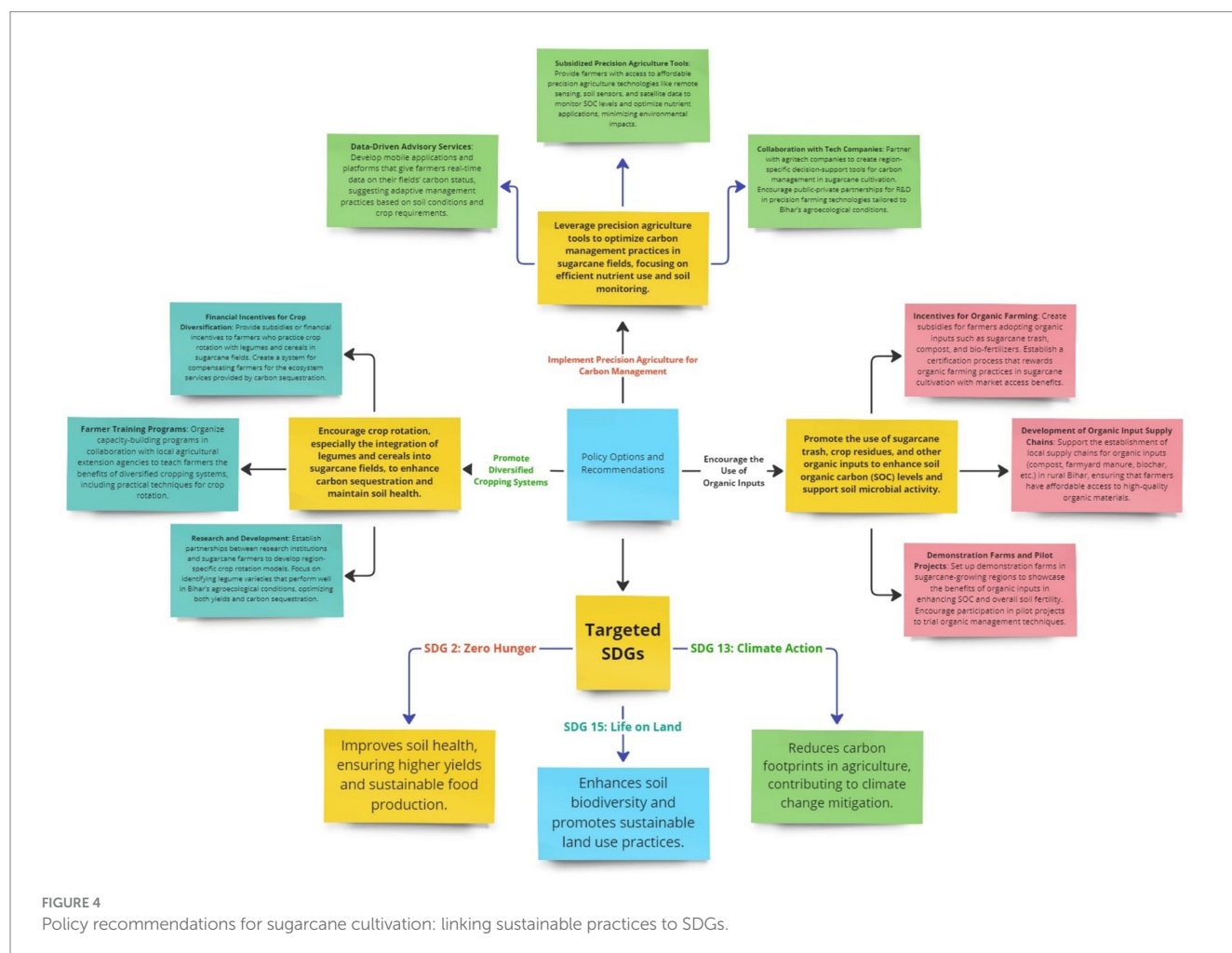
4 Policy recommendation

The policy recommendations in this study focus on promoting diversified cropping systems, encouraging the use of organic inputs, and implementing precision agriculture for effective carbon management (Figure 4). These strategies directly support key Sustainable Development Goals (SDGs). Improving soil health through crop rotations and organic practices directly supports SDG 2 (Zero Hunger) by increasing yields and promoting sustainable food production. At the same time, SDG 13 (Climate Action) is addressed through reduced carbon footprints and enhanced carbon

sequestration, contributing to climate change mitigation. Additionally, improved soil management practices that enhance biodiversity and promote sustainable land use align with SDG 15 (Life on Land), contributing to ecosystem resilience in sugarcane cultivation areas.

5 Conclusion

This study offers valuable insights into the dynamics of SOC in sugarcane cultivation under the agroecological conditions of Bihar, India. The findings revealed that carbon fractions are more concentrated in the surface soil layer, indicating the strong influence of adaptive management practices on enhancing carbon sequestration in the topsoil. The observed patterns in TOC and labile carbon pools emphasize the importance of targeted soil depth-specific interventions for improving soil health. These results underscore the potential of diversified practices to improve SOC distribution and contribute to sustainable land management and climate mitigation strategies. Crop rotations involving cereals and legumes showed enhanced biological activity, increased active carbon pools, and improved nutrient availability compared to continuous sugarcane cultivation, emphasizing the benefits of diversified cropping systems for sustainable soil health. These findings highlight the importance of diversified cropping systems to improve carbon fractions, boost biological activity, and ensure sustainable soil health long term.



Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding authors.

Author contributions

BK: Investigation, Writing – original draft, Writing – review & editing. SM: Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. AK: Resources, Supervision, Visualization, Writing – review & editing. VM: Formal analysis, Methodology, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. RL: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Adhikari, S., Moon, E., Paz-Ferreiro, J., and Timms, W. (2024). Comparative analysis of biochar carbon stability methods and implications for carbon credits. *Sci. Total Environ.* 914:169607. doi: 10.1016/j.scitotenv.2023.169607
- Basanta, M. V., Dourado-Neto, D., Reichardt, K., Bacchi, O. O. S., Oliveira, J. C. M., Trivelin, P. C. O., et al. (2003). Management effects on nitrogen recovery in a sugarcane crop grown in Brazil. *Geoderma* 116, 235–248. doi: 10.1016/S0016-7061(03)00103-4
- Batjes, N. H., Ribeiro, E., and van Oostrum, A. (2020). Standardised soil profile data to support global mapping and modelling (WoSIS snapshot 2019). *Earth Syst. Sci. Data* 12, 299–320. doi: 10.5194/essd-12-299-2020
- Benbi, D. K., Brar, K., Toor, A. S., and Singh, P. (2015). Total and labile pools of soil organic carbon in cultivated and undisturbed soils in northern India. *Geoderma* 237–238, 149–158. doi: 10.1016/j.geoderma.2014.09.002
- Bokhtiar, S. M., Paul, G. C., and Alam, K. M. (2008). Effects of organic and inorganic fertilizer on growth, yield, and juice quality and residual effects on ratoon crops of sugarcane. *J. Plant Nutr.* 31, 1832–1843. doi: 10.1080/01904160802325545
- Bonsucro (2023). The climate cane tracker: setting reduction targets for ghg emissions in sugarcane production. Available online at: <https://www.bonsucro.com/climatecane-tracker/> (Accessed 6 March, 2025).
- Bouma, J. (1989). “Using soil survey data for quantitative land evaluation” in *Advances in soil science*. ed. B. A. Stewart, vol. 9 (New York, NY: Springer), 177–213.
- Brejda, J. J., Moorman, T. B., Karlen, D. L., and Dao, T. H. (2000). Identification of regional soil quality factors and indicators i. central and southern High Plains. *Soil Sci. Soc. Am. J.* 64, 2115–2124. doi: 10.2136/sssaj2000.6462115x
- Chan, K. Y. (2001). Soil particulate organic carbon under different land use and management. *Soil Use Manag.* 17, 217–221. doi: 10.1111/j.1475-2743.2001.tb00030.x
- Chen, C., Riley, W. J., Prentice, I. C., and Keenan, T. F. (2022). CO₂ fertilization of terrestrial photosynthesis inferred from site to global scales. *Proc. Natl. Acad. Sci. USA* 119:e2115627119. doi: 10.1073/pnas.2115627119
- Cherubin, M. R., Carvalho, J. L. N., Cerri, C. E. P., Nogueira, L. A. H., Souza, G. M., and Cantarella, H. (2021). Land use and management effects on sustainable sugarcane-derived bioenergy. *Land* 10:72. doi: 10.3390/land10010072
- Cherubin, M. R., Karlen, D. L., Franco, A. L. C., Tormena, C. A., Cerri, C. E. P., Davies, C. A., et al. (2016). Soil physical quality response to sugarcane expansion in Brazil. *Geoderma* 267, 156–168. doi: 10.1016/j.geoderma.2016.01.004
- Choudhary, R. L., Wakchaure, G. C., Minhas, P. S., and Singh, A. K. (2017). Response of ratoon sugarcane to stubble shaving, off-barring, root pruning and band placement of basal fertilizers with a multipurpose drill machine. *Sugar Tech* 19, 33–40. doi: 10.1007/s12355-016-0438-x
- Datta, A., Basak, N., Chaudhari, S. K., and Sharma, D. K. (2015). Soil properties and organic carbon distribution under different land uses in reclaimed sodic soils of north-West India. *Geoderma Reg.* 4, 134–146. doi: 10.1016/j.geodrs.2015.01.006
- de la Rosa, D., and Sobral, R. (2008). “Soil quality and methods for its assessment” in *Land use and soil resources*. eds. A. K. Braimoh and P. L. G. Vlek (Dordrecht: Springer), 167–200.
- de Oliveira, I. N., Souza, Z. M., Bolonhezi, D., Totti, M. C. V., de Moraes, M. T., Lovera, L. H., et al. (2022). Tillage systems impact on soil physical attributes, sugarcane yield and root system propagated by pre-sprouted seedlings. *Soil Tillage Res.* 223:105460. doi: 10.1016/j.still.2022.105460
- Ding, G., Liu, X., Herbert, S., Novak, J., Amarasiwardena, D., and Xing, B. (2006). Effect of cover crop management on soil organic matter. *Geoderma* 130, 229–239. doi: 10.1016/j.geoderma.2005.01.019
- Amaral, W. A. N. do, Marinho, J. P., Tarasanchi, R., Beber, A., and Giuliani, E. (2008). Environmental sustainability of sugarcane ethanol in Brazil. In M. R. L. V. Leal and A. M. Walter (Eds.), *Sugarcane ethanol* (pp. 113–138). Wageningen, Netherlands: Wageningen Academic Publishers.
- Dotaniya, M. L., Datta, S. C., Biswas, D. R., and Kumar, K. (2014). Effect of organic sources on phosphorus fractions and available phosphorus in Typic Haplustepts. *J. Indian Soc. Soil Sci.* 62, 80–83.
- Ensinas, S. C., Serra, A. P., Marchetti, M. E., Da Silva, E. F., Ferreira do Prado, E. A., Lourente, E. R. P., et al. (2015). Effects of sugarcane cropping on organic carbon properties of the soil. *Aust. J. Crop. Sci.* 9, 1042–1048.
- Fan, L., Wigneron, J. P., Ciais, P., Chave, J., Brandt, M., Sitch, S., et al. (2023). Siberian carbon sink reduced by forest disturbances. *Nat. Geosci.* 16, 56–62. doi: 10.1038/s41561-022-01087-x

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1535741/full#supplementary-material>

- Gadge, S. K., Powar, M. S., and Jadhav, B. D. B. (2017). Sugarcane trash management for residue recycling and higher production. *Indian Farm.* 67, 45–46.
- Gunarathna, M. H. J. P., Sakai, K., Nakandakari, T., Momii, K., Onodera, T., Kaneshiro, H., et al. (2018). Optimized subsurface irrigation system: the future of sugarcane irrigation. *Water* 10:314. doi: 10.3390/w10030314
- Hanson, E., Nwakile, C., and Hammed, V. O. (2025). Carbon capture, utilization, and storage (CCUS) technologies: evaluating the effectiveness of advanced CCUS solutions for reducing CO₂ emissions. *Results Surf Interfaces* 18:100381. doi: 10.1016/j.rsufi.2024.100381
- Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil* 191, 77–87. doi: 10.1023/A:1004213929699
- Hillier, J., Hawes, C., Squire, G., Hilton, A., Wale, S., and Smith, P. (2009). The carbon footprints of food crop production. *Int. J. Agric. Sustain.* 7, 107–118. doi: 10.3763/ijas.2009.0419
- IPCC (2006) Guidelines for national greenhouse gas inventories. Available online at: <https://www.ipcc-nggip.iges.or.jp/public/2006gl/> (Accessed January 12, 2025).
- IPCC (2021). Climate change the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Available online at: <https://www.ipcc.ch/report/ar6/wg1/> (Accessed March 6, 2025).
- Islam, K. R., and Weil, R. R. (2000). Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. *Agric. Ecosyst. Environ.* 79, 9–16. doi: 10.1016/S0167-8809(99)00145-0
- ISO (2022) International sugar organization (ISO). Climate change and sugarcane: impacts and adaptation strategies. Available online at: <https://www.isosugar.org/publications> (Accessed January 11, 2025).
- Jackson, M. L. (1973). Soil chemical analysis. Prentice Hall of India Pvt Ltd: New Delhi.
- Jha, C. K., Sinha, S. K., and Thakur, S. K. (2017). Enhancing soil fertility, nutrient uptake and sugarcane productivity through integrated use of Fe and organics in sub-tropical system. *Indian J. Ecol.* 44, 521–525.
- Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., and Schuman, G. E. (1997). Soil quality: a concept, definition, and framework for evaluation (a guest editorial). *Soil Sci. Soc. Am. J.* 61, 4–10. doi: 10.2136/sssaj1997.03615995006100010001x
- Knoepf, J. D., and Swank, W. T. (1997). Forest management effects on surface soil carbon and nitrogen. *Soil Sci. Soc. Am. J.* 61, 928–935. doi: 10.2136/sssaj1997.03615995006100030031x
- Kumar, N., Singh, A. K., Kamat, D. N., Kumar, A., Minnatullah, M. D., Kumar, A., et al. (2023). Sustainable sugarcane production and utilization: Issues and initiatives (souvenir-cum-edited book). Annual group Meet-2023, all India coordinated research project on sugarcane, October 26–27, 2023. SRI, RPCAU, Pusa, Bihar, India, 1–256.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627. doi: 10.1126/science.1097396
- Lu, M., Wang, M., Sun, Y., Sun, G., Zhao, D., San, S., et al. (2024). Low rather than high level nitrogen additions accelerate carbon release process and inhibit recalcitrant carbon allocation via stirring soil enzymatic activities in plateau meadows. *J. Soil Sci. Plant Nutr.* 24, 3087–3099. doi: 10.1007/s42729-024-01734-9
- Majumder, B., Mandal, B., and Bandyopadhyay, P. K. (2008). Soil organic carbon pools and productivity in relation to nutrient management in a 20-year-old rice–berseem agroecosystem. *Biol. Fertil. Soils* 44, 451–461. doi: 10.1007/s00374-007-0226-6
- Meena, V. S., Ghosh, B. N., Singh, R. J., Bhattacharyya, R., Sharma, N. K., Alam, N. M., et al. (2021). Land use types and topographic position affect soil aggregation and carbon management in the mountain agro-ecosystems of the Indian Himalayas. *Land Degrad. Dev.* 32, 3992–4003. doi: 10.1002/ldr.3864
- Meena, V. S., Mondal, T., Pandey, B. M., Mukherjee, A., Yadav, R. P., Choudhary, M., et al. (2018). Land use changes: strategies to improve soil carbon and nitrogen storage pattern in the mid-Himalaya ecosystem, India. *Geoderma* 321, 69–78. doi: 10.1016/j.geoderma.2018.02.002
- Meena, R. S., Pradhan, G., Singh, K., Kumar, S., Singh, A. K., Shashidhar, K. S., et al. (2024). Agriculture models for restoring degraded land to enhance CO₂ biosequestration and carbon credits in the Vindhyan region of India. *Sci. Total Environ.* 929:172661. doi: 10.1016/j.scitotenv.2024.172661
- Mir, Y. H., Ganie, M. A., Shah, T. I., Aezum, A. M., Bangroo, S. A., Mir, S. A., et al. (2023). Soil organic carbon pools and carbon management index under different land use systems in northwestern Himalayas. *PeerJ* 11:e15266. doi: 10.7717/peerj.15266
- More, N. B., Bhalerao, V. P., Phalke, D. H., Patil, A. V., and Bhoi, P. G. (2007). Nitrogen economy by using green manuring intercrops in pre seasonal sugarcane. *Indian Sugar* 57, 39–45.
- Mthimkhulu, S. S., Modi, A. T., and Mabhaudhi, T. (2016). The effect of integrated soil fertility management on maize (*Zea mays* L.) yield and soil chemical properties in a smallholder farming system in South Africa. *Nutr. Cycl. Agroecosyst.* 106, 43–57. doi: 10.1007/s10705-016-9781-4
- Needelman, B. A., Wander, M. M., Bollero, G. A., Boast, C. W., Sims, G. K., and Bullock, D. G. (1999). Interaction of tillage and soil texture biologically active soil organic matter in Illinois. *Soil Sci. Soc. Am. J.* 63, 1326–1334. doi: 10.2136/sssaj1999.6351326x
- Nie, X., Wang, H., Wang, J., and Liu, S. (2024). Natural forests exhibit higher organic carbon concentrations and recalcitrant carbon proportions in soil than plantations: a global data synthesis. *J. For. Res.* 35:90. doi: 10.1007/s11676-024-01739-1
- OECD/FAO (2019). OECD-FAO Agricultural Outlook 2019–2028. Rome: OECD Publishing.
- Ozlu, E., Arriaga, F. J., Bilen, S., Gozukara, G., and Babur, E. (2022). Carbon footprint management by agricultural practices. *Biology* 11:1453. doi: 10.3390/biology11101453
- Paustian, K., Six, J., Elliott, E. T., and Hunt, H. W. (2000). Management options for reducing CO₂ emissions from agricultural soils. *Biogeochemistry* 48, 147–163. doi: 10.1023/A:1006271331703
- PIB (2022). India emerges as world's largest sugar producer and consumer. Press Information Bureau, Government of India. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=1865320> (Accessed October 5, 2022).
- Poepplau, C., and Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – a meta-analysis. *Agric. Ecosyst. Environ.* 200, 33–41. doi: 10.1016/j.agee.2014.10.024
- Powar, R. V., Patil, D. B., Powar, T. R., and Bandgar, P. S. (2021). Assessment of farmers' knowledge and perception towards the usage of sugarcane trash and environmental safety. *Res. Squ.* doi: 10.21203/rs.3.rs-1210067/v1
- Ravikumar, V., Vijayakumar, G., Šimůnek, J., Chellamuthu, S., Santhi, R., and Appavu, K. (2011). Evaluation of fertigation scheduling for sugarcane using a vadose zone flow and transport model. *Agric. Water Manag.* 98, 1431–1440. doi: 10.1016/j.agwat.2011.04.012
- Regnier, P., Resplandy, L., Najjar, R. G., and Ciais, P. (2022). The land-to-ocean loops of the global carbon cycle. *Nature* 603, 401–410. doi: 10.1038/s41586-021-04339-9
- Rezapour, S., and Samadi, A. (2012). Assessment of soil quality indicators in different agricultural lands in northwest of Iran. *J. Soil Sci. Plant Nutr.* 12, 689–705. doi: 10.4067/S0718-95162012005000006
- Shanthi, T. R., Gurumurthy, D., and Saravanan, L. (2020). Trash management practices in sugarcane cultivation: A socio-economic analysis. *Indian Res. J. Extens. Educ.* 20, 1–8. doi: 10.29005/irjee.2020.20.4.1
- Sherrrod, L. A., Peterson, G. A., Westfall, D. G., and Ahuja, L. R. (2005). Soil organic carbon pools after 12 years in no-till dryland agroecosystems. *Soil Sci. Soc. Am. J.* 69, 1600–1608. doi: 10.2136/sssaj2003.0266
- Sinha, S. K., Jha, C. K., Kumar, V., and Pandey, S. S. (2017a). Yield and soil organic carbon pool in relation to soil fertility of sugarcane (*Saccharum* species hybrid complex) plant-ratoon system under integrated nutrient management. *Indian J. Agron.* 62, 25–30. doi: 10.59797/ija.v62i1.4269
- Sinha, S. K., Kumar, V., and Jha, C. K. (2017b). Effect of integrated use of bio-compost and nitrogen on productivity and soil properties of sugarcane plant-ratoon system in calcareous soil. *Sugar Tech.* 19, 485–491. doi: 10.1007/s12355-016-0501-7
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., et al. (2008). Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 789–813. doi: 10.1098/rstb.2007.2184
- Solomon, S. (2016). Sugarcane production and development of sugar industry in India. *Sugar Tech* 18, 588–602. doi: 10.1007/s12355-016-0494-2
- Suma, R., and Savitha, C. M. (2015). Integrated sugarcane trash management: a novel technology for sustaining soil health and sugarcane yield. *Adv. Crop. Sci. Tech.* 3, 1–4. doi: 10.4172/2329-8863.1000160
- Surendran, U., Ramesh, V., Jayakumar, M., Marimuthu, S., and Sridevi, G. (2016). Improved sugarcane productivity with tillage and trash management practices in semi arid tropical agro ecosystem in India. *Soil Tillage Res.* 158, 10–21. doi: 10.1016/j.still.2015.10.009
- Tubiello, F., Conchedda, G., Wanner, N. S., Federici, S., Rossi, S., and Grassi, G. (2021). Carbon emissions and removals from forests: new estimates, 1990–2020. *Earth Syst. Sci. Data* 13, 1681–1691. doi: 10.5194/essd-13-1681-2021
- Tubiello, F. N., Salvatore, M., Córdor Golec, R. D., Ferrara, A., Rossi, S., Biancalani, R., et al. (2014). Agriculture, forestry and other land use emissions by sources and removals by sinks (FAO statistics division working paper series No. 2): Food and Agriculture Organization of the United Nations, 3–20.
- Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., and Govaerts, B. (2015). Crop residue management and soil health: a systems analysis. *Agric. Syst.* 134, 6–16. doi: 10.1016/j.agry.2014.05.009
- Wakchaure, G. C., Minhas, P. S., Biswas, A. K., Meena, K. K., Pradhan, A., Gawhale, B. J., et al. (2025). Assessment of gains in productivity and water-energy-carbon nexus with tillage, trash retention and fertigation practices in drip irrigated sugarcane. *Renew. Sustain. Energy Rev.* 211:115294. doi: 10.1016/j.rser.2024.115294
- Walkley, A., and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38. doi: 10.1097/00010694-193401000-00003
- Weil, R., Islam, K. R., Stine, M. A., Gruver, J. B., and Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: a simple method for laboratory and field use. *Am. J. Altern. Agric.* 18, 3–17. doi: 10.1079/AJAA2003003
- Wieder, W. R., Cleveland, C. C., Smith, W. K., and Todd-Brown, K. (2015). Future productivity and carbon storage limited by terrestrial nutrient availability. *Nat. Geosci.* 8, 441–444. doi: 10.1038/ngeo2413

Yang, X., Zhang, S., Wu, D., Huang, Y., Zhang, L., Liu, K., et al. (2024). Recalcitrant components accumulation in dissolved organic matter decreases microbial metabolic quotient of red soil under long-term manuring. *Sci. Total Environ.* 934:173287. doi: 10.1016/j.scitotenv.2024.173287

Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A., et al. (2015). Evolution of water lifting devices (pumps) over the centuries worldwide. *Water* 7, 5031–5060. doi: 10.3390/w7095031