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Long-term Impact of Crop Residue Management on Lability and Thermal Sensitivity of Soil Organic Carbon under Wheat Based Cropping Systems

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ABSTRACT

The study was conducted beginning from 2009 to 2020 (11 years) at ICAR-Indian Agricultural Research Institute, New Delhi, India to evaluate the long-term effects of various residue management practices (RMPs) on soil organic carbon (SOC) fractions in wheat based cropping systems in north-western India. A split-split plot design included four RMPs: biochar (BC) application, crop residue incorporation (CRI), crop residue burning (CRB), and complete residue removal (CRR), applied across three cropping systems: wheat-maize (WMCS), wheat–pearl millet (WPCS), and wheat–rice (WRCS). The study examined SOC mineralization, particulate organic matter carbon (POM-C), and oxidizable organic carbon (OOC) fractions. The findings reveal that BC application significantly enhances the stability of SOC, as evident from the higher activation energy (Ae) and Q_{10} values, particularly in macroaggregates across different soil depths. Regardless of the cropping systems, the plots treated with BC had the largest percentage of macroaggregate associated POM-C in both the soil depths, specifically 5.67 g kg^{-1} at 0–15 cm and 2.41 g kg^{-1} at 15–30 cm. Furthermore, the findings demonstrated that the application of crop residue incorporation (CRI) and BC treatments consistently increase the amount of higher labile carbon (C) available in the soil, hence promoted nutrient cycling and microbial activity. In contrast, CRB and CRR treatments showed lower SOC stability and labile C contents. These results highlight BC's potential as a sustainable residue management strategy (RMP) for boosting soil health and SOC sequestration in wheat based cropping systems.

KEYWORDS: Biochar, crop residue, labile carbon, residue burning

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1. INTRODUCTION

Global efforts to ensure food security and combat climate change underscore the vital role of soil organic carbon (SOC) sequestration in climate change mitigation, although its stability under changing thermal conditions remains uncertain (Das et al., 2023). In South Asia, particularly in north-western India, SOC depletion has become a critical concern (Kalaiselvi et al., 2023) due to unsustainable agricultural practices which has degraded soil health. The continuous cultivation of wheat-based systems, particularly the prevalent rice–wheat rotation (Parihar et al., 2016 and Nawaz et al., 2019), has led to declining soil productivity and diminished resource–use efficiency (Sharma et al., 2012). This decline is further aggravated by poor crop residue management practices (RMPs), which have reduced soil organic matter (SOM) levels. In India, cereal crops like rice, wheat, maize, and millets contribute nearly 70% of the country's crop residues, with rice and wheat combinedly accounting for over half of the share (Bhatt et al., 2023). In regions such as Punjab, Haryana, and western Uttar Pradesh, the overwhelming volume of post-harvest crop residues has become difficult to manage, leading to widespread burning-a practice that not only erodes soil fertility but also significantly contributes to air pollution (Ravindra et al., 2023). Modern agricultural practices often involve leaving crop residues on the soil surface or incorporating them through tillage (Purakayastha et al., 2008). Tillage-based residue incorporation boosts C sequestration, but in intensive cropping systems, the high volume of residues and their slow decomposition make this approach impractical. Biochar (BC) on the other hand offers a sustainable alternative to burning. It improves soil quality, boosts crop productivity, and acts as a carbon sink, thereby enhancing climate resilience and contributing significantly to C sequestration (Purakayastha et al., 2019; Elkhlifi et al., 2023).

The temperature sensitivity of SOC, assessed through the Q_{10} value, indicates how SOC mineralization rates change with a 10°C temperature rise (Liu et al., 2017). This sensitivity is complex due to the diverse kinetic properties of SOM. Research on SOC temperature sensitivity shows varied results, with few suggesting that recalcitrant carbon is less sensitive to temperature changes (Kleber, 2010), while report that non-labile SOC may be more responsive than labile SOC (Parihar et al., 2019), or that both types show similar sensitivity (Lefevre et al., 2014). The effects of cropping systems and residue management on SOC protection are significant, as the type and amount of residue influence SOM's biochemical composition and stability under temperature changes. It is vital to assess the impact of management practices on C accumulation under different OC fractions in soil. Soil C accumulation differs from sequestration, where positive total SOC change is accumulation, while sequestration involves long-lived C pools (recalcitrant pools). Understanding these dynamics is essential because labile C pools affect soil health and economic benefits, while recalcitrant pools are crucial for long-term C-sequestration.

We hypothesized that long-term crop RMPs, including BC application, crop residue incorporation (CRI), crop residue burning (CRB), and crop residue removal (CRR) might significantly affect the stability and quality of SOC across three wheat based cropping systems {wheat–maize (WMCS), wheat–pearl millet (WPCS), and wheat–rice (WRCS)}. These effects are driven by changes in SOC mineralization and oxidizable SOC fractions, which are essential for understanding SOC sequestration mechanisms and assessing overall environmental health in Inceptisol of north-western India. The study aims to evaluate the long-term impacts of these RMPs on SOC mineralization and oxidizable SOC fractions within these cropping systems.

2. MATERIALS AND METHODS

2.1. Treatment details

The study is part of a long-term residue management experiment that is going on since 2009 in the research farm of IARI, New Delhi. The experiment involved three wheat-based cropping systems, viz., wheat (*Triticum aestivum*, cv HD 2967), pearl millet (*Pennisetum glaucum*, cv Pusa composite 1601), wheat-maize (*Zea mays* L., cv PMH-10), and rice (*Oryza sativa* L., cv Pusa Basmati 1121). The soil in the experimental area was sandy loam in texture, with a pH of 8.1 and can be taxonomically named as Typic Haplustept (Purakayastha et al., 2008). The main plot consisted of different wheat based cropping systems: wheat–maize (WMCS), wheat–pearl millet (WPCS), and wheat–rice (WRCS). The subplots received different residue management treatments, which included: a) biochar (BC), b) crop residue incorporation (CRI), c) crop residue burning (CRB), d) crop residue removal (CRR). Each treatment was replicated three times, and the plot size was 5×3.5 m^2. In the CRR treatment, all crop residues were completely removed from the field. On the other hand, in the CRI treatment, crop residues were chopped into small pieces and mixed into the soil at a depth of 15 cm before sowing or transplanting the next crop. To prepare the field, several ploughings were done in July 2018, using a tractor-mounted rotavator and cultivator. Puddling was carried out at optimum moisture conditions by repeated ploughing before transplanting the rice crop. Standard cropping methods were followed for fertilization (Pathak et al., 2003), and irrigation was provided twice in a week except. Wheat was cultivated as a winter crop from November to March, while maize, rice, and pearl millet were grown as wet season crops from June/ July to September/October.

2.2. Soil sampling and processing

In April 2019, after the harvest of wheat crop, soil samples in triplicate were collected from three different depths (0–15 cm, 15–30 cm, and 30–60 cm). During soil sampling, gravels and visible pieces of crop residues were removed, and the samples were divided into three portions. One portion was used for aggregate analysis using Yoder's apparatus (Yoder, 1936). Large clods were broken by hand into smaller segments along natural cleavage before air-dried soil was sieved to obtain aggregates that passed through 8 mm and retained on 2 mm sieve. After wet-sieving, aggregates from each sieve were transferred to a set of pre-weighed beakers, oven dried at 60°C until water evaporated and weighed. The sizes of the aggregate fractions, specifically macroaggregate (2.0–0.25 mm) and microaggregate (0.25–0.053 mm), resulting from the wet sieving process were determined.

2.3. Soil organic carbon mineralization

Laboratory incubation was carried out to find the C mineralization in the treatments of different cropping systems and residue management options. Soil samples from three depths (0–15, 15–30, and 30–60 cm) were incubated for 60 days under three temperature conditions viz. 25, 30, and 35°C. Soil was moistened to reach a field capacity state. Forty grams of soil (on oven dry basis) at field capacity was taken in glass jar (500 ml) containing 0.1N NaOH in a vial to trap CO_2 evolved from the soil (Zibilske, 1994). The alkali was replaced twice in the first 2 weeks' period followed by once in a week for the rest of the incubation period. The unreacted alkali was back-titrated with standard HCl to estimate the CO_2-C evolved from soil.

The equation used for CO_2 measurement periodically is given below:

CO_2-C evolved (mg kg^{-1})=(A–B)×N×6

Where A and B are the volume (ml) of HCl consumed for titrating 5 ml of 0.5 N NaOH in control (without soil) and soil, respectively. N is the normality of HCl, and 6 is the equivalent weight of C.

Temperature sensitivity of C loss was calculated by using Arrhenius equation (Eq 1) and Q_{10} values (Knorr et al., 2005).

$$k = A \times \exp(-Ae/RT)$$

Where k =Reaction rate, Ae=Activation energy, A=Factor, R=Universal gas constant, T=Absolute temperature

Taking the natural logarithmic form of Arrhenius equation:

$$\ln(k) = -Ae/(RT) + \ln(A)$$

So, when a reaction has a rate constant that obeys Arrhenius equation, a plot of ln(k) versus 1/T gives a straight line, and the gradient and intercept were used to determine Ae and A. The activation energy is (-R) times the slope of a plot of ln(k) vs (1/T). Then the temperature sensitivity (Q_{10}) of SOC mineralization was estimated.

2.4. Particulate organic matter carbon (POM-C)

The particulate organic matter carbon (POM-C) was separated from the microaggregate and macroaggregate samples using the procedure outlined by Camberdella and Elliot (1992). Sodium hexametaphosphate (0.5%) was added to 10 g soil (air dried and passed through 2 mm sieved) and was shaken on rotary for 15 hours. Then the soil suspension was passed through 0.053 mm sieve using a mild jet of water from the top of the sieve. The solid portion retained on the sieve was transferred to pre-weighed filter paper by washing with water. It contained both particulate organic matter and sand particles. The filter papers were oven dried (50°C for 72 hours), and the weights were recorded. The solid materials in the filter paper were ground in a pestle and mortar to make it a fine powder. The materials were passed through 0.2 mm sieve, and total Carbon content in POM (POM-C) was determined by dry combustion method in a CHNS analyser (Euro Vector make, Euro EA3000 model).

2.5. Oxidizable soil organic carbon and its fractions

Oxidizable organic carbon (OOC) and its different pools in the soil were estimated using Walkley and Black (1934) method as modified by Chan et al. (2001). Total SOC was divided into four pools of decreasing oxidizability (Chan et al., 2001). These pools are designated as follows: Pool I (very labile OC; VLC), Pool II (labile OC; LC), Pool III (less labile OC; LLC), and Pool IV (non-labile OC; NLC). Pools I and II together constitute the labile pool, while Pools III and IV constitute together the recalcitrant pool (Chan et al., 2001).

2.6. Statistical analysis

The statistical analysis was done using Analysis of Variance (ANOVA) in a split-plot design, as described by Gomez and Gomez (1984). The main plot in this study was the cropping systems, whereas the subplot was the RMPs. The treatment means were statistically compared at a significance threshold of $p<0.05$ using the least significant difference (LSD) method for all the parameters. The data underwent a separation of means analysis using Tukey's honestly significant difference (HSD) approach.

3. RESULTS AND DISCUSSION

3.1. Temperature sensitivity of SOC and mineralization

The significance of the interaction between wheat–based cropping systems and RMPs was observed in relation to both the Ae and Q_{10} of the thermodynamic parameters. At the 0–15 cm soil depth, the Ae in macroaggregates was significantly higher under the WP–BC treatment (62.6 kJ mol^{-1}), followed by WM–BC (53.5 kJ mol^{-1}) and WR–BC (43.2 kJ mol^{-1}). Among cropping systems, WP showed the highest Ae (38.07 kJ mol^{-1}), while WR recorded the lowest (27.83 kJ mol^{-1}). In the 15–30 cm depth, Ae in macroaggregates was highest under BC treatments across all cropping systems, with the maximum value recorded for WR–BC (65.1 kJ mol^{-1}). WP (54.3 kJ mol^{-1}) outperformed WM (49.7 kJ mol^{-1}) and WR (45.9 kJ mol^{-1}). For microaggregates, the Ae was significantly higher under CRI in WR (84.09 kJ mol^{-1}) compared to other treatments. At the 30–60 cm depth, macroaggregates under WM–BC exhibited the highest Ae (61.2 kJ mol^{-1}), followed by WR–CRI (59.8 kJ mol^{-1}) and WP–CRR (51.8 kJ mol^{-1}). For microaggregates, WP–CRI (38.7 kJ mol^{-1}) and WP–BC (52.7 kJ mol^{-1}) showed notable Ae values compared to other treatments (Table 1). The Q_{10} values were calculated by using Kc values at various temperatures. Similarly, Q_{10} value was also significantly higher in macroaggregate fraction of BC treated plots regardless of cropping system practices considered in all soil depths; similar trend was observed in the case of microaggregate fractions except in 30–60 cm soil depth where significantly higher values were observed under WM–CRI plot (Table 2).

The Ae values, which indicated the resistance of C to thermal degradation, were notably higher in WM–BC treated plots compared to other treatments. This implies that SOC in these plots is more resistant to decomposition, indicating greater long-term stability of C. Similarly, the Q_{10} values, which represented the temperature sensitivity

Table 1: Effect of long-term residue management practices on activation energy (Ae) of SOC in soil under wheat based cropping systems

Treatments	Macroaggregates (kJ mol^{-1})			Microaggregates (kJ mol^{-1})		
	0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm
Cropping systems						
WM	37.51^{a}	49.7^{b}	37.0^{a}	48.5^{a}	48.9^{c}	43.5^{a}
WP	38.07^{a}	54.3^{a}	30.1^{b}	40.4^{b}	53.2^{b}	37.8^{b}
WR	27.83^{b}	45.9^{c}	29.7^{b}	34.7^{c}	54.4^{a}	30.5^{c}
Residue management practices						
BC	53.1^{a}	65.1^{a}	38.9^{a}	54.7^{a}	58.5^{b}	52.6^{a}
CRI	36.8^{b}	57.5^{b}	32.9^{b}	45.0^{b}	71.1^{a}	46.2^{b}
CRB	24.0^{c}	44.2^{c}	32.8^{b}	32.9^{c}	40.4^{c}	30.2^{c}
CRR	23.8^{c}	33.0^{d}	24.4^{c}	32.2^{c}	38.7^{d}	20.1^{d}
Cropping systems×residue management practices						
WM–BC	53.5^{b}	65.1^{a}	61.2^{a}	53.7^{c}	52.7^{d}	52.6^{b}
WM–CRI	43^{c}	53.3^{b}	30.7^{d}	65.58^{b}	64.6^{c}	83.1^{a}
WM–CRB	22.2^{g}	36.1^{e}	30.6^{d}	53.6^{c}	42.6^{e}	8.07^{g}
WM–CRR	31.2^{e}	39.4^{d}	25.3^{e}	26.02^{e}	35.8^{f}	30.4^{d}
WP–BC	62.6^{a}	53.7^{b}	38.6^{c}	70.8^{a}	69.87^{b}	52.7^{b}
WP–CRI	36.1^{d}	45.3^{c}	7.97^{h}	53.7^{c}	64.5^{c}	38.7^{c}
WP–CRB	22.1^{g}	31.3^{f}	21.7^{f}	39.5^{d}	42.7^{e}	52^{b}
WP–CRR	31.3^{e}	31.4^{f}	51.8^{b}	53.7^{c}	35.9^{f}	8.01^{g}
WR–BC	43.2^{c}	45.4^{c}	16.8^{g}	71.04^{a}	52.8^{d}	52.9^{b}
WR–CRI	31.4^{e}	36.3^{e}	59.8^{a}	53.6^{c}	84.09^{a}	16.8^{f}
WR–CRB	27.5^{f}	31.2^{f}	20.7^{f}	39.6^{d}	35.9^{f}	30.7^{d}
WR–CRR	9.11^{h}	25.7^{g}	21.5^{f}	19.4^{f}	44.7^{e}	21.8^{e}

WM: wheat–maize; WP: Wheat–pearl millet; WR: Wheat–rice; BC: Biochar; CRI: Crop residue incorporation; CRB: Crop residue burning; CRR: Crop residue removal. The presence of identical letters within each column indicates that, based on the least significant difference test, there are no significant differences among the treatments (p<0.05)

of SOC decomposition, were also higher in BC treated plots, further supporting the enhanced thermal stability of C under WM–BC treatment. This suggested that BC application could positively influence the stability of C in the soil, reducing the risk of C loss through decomposition. The study found that Ae and Q_{10} values were higher in macroaggregates than in microaggregates which indicates that C protected within macroaggregates is more recalcitrant than C in microaggregates (Ghosh et al., 2018, Bhattacharyya et al., 2023). The diverse outcomes revealed that the temperature sensitivity of SOM decomposition was regulated by intricate mechanisms reliant on organo-mineral interactions, the SOM quality, and abiotic factor like moisture content. Additionally, the desorption of sorbed C from minerals at higher temperatures might contribute to the accelerated decomposition of C from macroaggregates under residue treatment (Six et al., 2002). The higher Q_{10} values indicated the higher temperature sensitivity and hence could be more useful in generating positive feedback for global warming.

3.2. Particulate organic matter-carbon (POM-C)

The POM-C content was determined to assess the amount of carbon associated with the POM fraction. It helped in understanding the potential for C sequestration and its physical stability within the soil. The results from Table 3 showed that there were significant variations in POM-C within the macroaggregates due to different cropping systems and RMPs. The WMCS plots had significantly higher levels of macroaggregate associated POM-C in all soil depths compared to the WPCS and WRCS plots, which increased in the range of ~5–13 %, ~7–23%, and ~13–51 % in

Table 2: Effect of long-term residue management practices on Q_{10} of SOC in soil under wheat based cropping systems

Treatments	Macroaggregates			Microaggregates		
	0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm
Cropping systems						
WM	1.66[b]	1.84[b]	1.64[a]	1.91[a]	1.91[c]	1.85[a]
WP	1.68[a]	1.94[a]	1.51[b]	1.71[b]	2.03[a]	1.64[b]
WR	1.46[c]	1.77[c]	1.51[b]	1.59[c]	1.92[b]	1.48[c]
Residue management practices						
BC	1.93[a]	2.23[a]	1.70[a]	2.06[a]	2.15[b]	1.94[a]
CRI	1.71[b]	2.01[b]	1.59[b]	1.81[b]	2.32[a]	1.91[a]
CRB	1.38[c]	1.69[c]	1.37[d]	1.54[c]	1.69[c]	1.49[b]
CRR	1.37[c]	1.48[d]	1.56[c]	1.53[c]	1.66[d]	1.27[c]
Cropping systems×residue management practices						
WM–BC	2.02[a]	1.90[c]	2.27[a]	2.35[a]	1.99[c]	1.94[b]
WM–CRI	1.76[c]	2.22[b]	1.48[d]	2.02[b]	2.32[b]	2.92[a]
WM–CRB	1.34[g]	1.90[c]	1.48[d]	1.61[e]	1.74[e]	1.081[g]
WM–CRR	1.51[e]	1.33[e]	1.38[e]	1.68[d]	1.59[f]	1.46[d]
WP–BC	2.27[a]	2.38[a]	1.65[c]	2.02[b]	2.49[a]	1.94[b]
WP–CRI	1.61[d]	1.90[c]	1.10[h]	1.81[c]	2.32[b]	1.62[c]
WP–CRB	1.34[g]	1.58[d]	1.32[f]	1.51[f]	1.74[e]	1.94[b]
WP–CRR	1.51[e]	1.90[c]	1.98[b]	1.51[f]	1.59[f]	1.081[g]
WR–BC	1.51[e]	2.38[a]	1.23[g]	1.81[c]	1.99[c]	1.94[b]
WR–CRI	1.76[c]	1.90[c]	2.20[a]	1.61[e]	2.32[b]	1.21[f]
WR–CRB	1.44[f]	1.58[d]	1.30[f]	1.51[f]	1.59[f]	1.46[d]
WR–CRR	1.13[h]	1.22[f]	1.32[f]	1.41[g]	1.79[d]	1.29[e]

WM: wheat–maize; WP: Wheat–pearl millet; WR: Wheat–rice; BC: Biochar; CRI: Crop residue incorporation; CRB: Crop residue burning; CRR: Crop residue removal. The presence of identical letters within each column indicates that, based on the least significant difference test, there are no significant differences among the treatments (p<0.05)

0–15 cm, 15–30 cm, and 30–60 cm soil depths, respectively. Among the RMPs, the BC treated plots had the highest percentage of macroaggregate associated POM-C in both soil depths, with 5.67 g kg^{-1} in the 0–15 cm and 2.41 g kg^{-1} in the 15–30 cm. On the other hand, the CRR residue treated plots had the lowest macroaggregate associated POM-C in all soil depths. As far as the effect of RMPs on cropping systems is concerned, the POM-C content in microaggregates in the WM plots was significantly higher (3.57 g kg^{-1}) than in WRCS plots (2.62 g kg^{-1}) in the 0–15 cm soil layer. RMPs also had a significant effect on POM-C within microaggregates. In the 0–15 cm soil depth, the BC treatment had the highest microaggregate associated POM-C (4.28 g kg^{-1}), followed by CRI (3.50 g kg^{-1}) and CRB (2.35 g kg^{-1}). The same trend was also observed in the 30–60 cm soil depth. However, the microaggregate associated POM-C was generally lower in the subsurface soil layers than in the surface 0–15 cm soil layer, regardless of cropping system and RMPs.

POM-C is an important indicator of labile SOC, representing the active C fraction within soil. It predominantly consisted of recognizable plant-derived remains, including fungal spores, hyphae, and charcoal (Gregorich et al., 1995), which were commonly associated with macroaggregates (Six et al., 1998). This macroaggregate association provided physical protection to the POM-C, preventing rapid decomposition and contributing to soil stability. The relatively labile nature of POM-C was attributed to its recent origin, often from plant residues and microbial biomass. In the present study, WMCS and BC treatments led to higher POM-C levels, particularly within the macroaggregates, indicating enhanced C sequestration and soil stability. These

Table 3: Effect of long-term residue management practices on particulate organic matter carbon (POM-C) in soil under wheat based cropping systems

Treatments	Macroaggregates (g kg^{-1})			Microaggregates (g kg^{-1})		
	0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm
Cropping systems						
WM	4.56^{a}	2.22^{a}	0.59^{a}	3.57^{a}	0.81^{a}	0.30^{a}
WP	4.34^{b}	2.07^{b}	0.52^{b}	3.17^{b}	0.78^{a}	0.27^{b}
WR	3.13^{c}	1.81^{c}	0.39^{c}	2.62^{c}	0.68^{b}	0.21^{c}
Residue management practices						
BC	5.67^{a}	2.41^{a}	0.52^{a}	4.28^{a}	0.78^{a}	0.27^{a}
CRI	3.99^{b}	2.30^{b}	0.51^{b}	3.50^{b}	0.77^{a}	0.26^{b}
CRB	3.23^{c}	1.71^{c}	0.50^{b}	2.35^{c}	0.75^{b}	0.26^{c}
CRR	3.14^{c}	1.70^{c}	0.47^{c}	2.35^{c}	0.74^{b}	0.24^{d}
Cropping systems×residue management practices						
WM–BC	6.40^{a}	2.39^{b}	0.53^{de}	5.03^{a}	0.81^{c}	0.27^{d}
WM–CRI	4.72^{c}	2.64^{a}	0.58^{c}	4.25^{b}	0.73^{f}	0.23^{g}
WM–CRB	3.47^{de}	1.90^{d}	0.68^{a}	2.05^{f}	0.85^{b}	0.29^{c}
WM–CRR	3.67^{d}	1.94^{d}	0.55^{d}	2.94^{d}	0.75^{de}	0.27^{d}
WP–BC	5.82^{b}	2.28^{bc}	0.65^{b}	4.14^{b}	0.75^{de}	0.30^{bc}
WP–CRI	4.64^{c}	2.56^{a}	0.52^{e}	3.47^{c}	0.86^{ab}	0.32^{a}
WP–CRB	3.58^{d}	1.73^{f}	0.44^{f}	2.69^{d}	0.88^{a}	0.31^{b}
WP–CRR	3.30^{e}	1.69^{e}	0.46^{f}	2.39^{e}	0.76^{d}	0.26^{e}
WR–BC	4.79^{c}	2.25^{c}	0.41^{g}	3.66^{c}	0.67^{g}	0.24^{f}
WR–CRI	2.61^{fg}	2.02^{d}	0.41^{g}	2.78^{d}	0.72^{f}	0.22^{h}
WR–CRB	2.38^{g}	1.50^{f}	0.39^{hi}	2.31^{e}	0.60^{h}	0.18^{i}
WR–CRR	2.73^{f}	1.46^{f}	0.40^{gh}	1.71^{g}	0.73^{ef}	0.21^{h}

WM: wheat–maize; WP: Wheat–pearl millet; WR: Wheat–rice; BC: Biochar; CRI: Crop residue incorporation; CRB: Crop residue burning; CRR: Crop residue removal. The presence of identical letters within each column indicates that, based on the least significant difference test, there are no significant differences among the treatments (p<0.05)

Table 4: Effect of long-term residue management practices on oxidizable soil carbon fractions under wheat based cropping systems

Treatments	Oxidizable soil carbon fractions											
	VLC (g kg^{-1})			LC (g kg^{-1})			LLC (g kg^{-1})			NLC (g kg^{-1})		
	0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm	0–15 cm	15–30 cm	30–60 cm
Cropping systems	Macroaggregates											
WM	2.22^{a}	1.29^{a}	1.09^{a}	1.57^{b}	0.32^{b}	0.16^{a}	1.10^{b}	0.99^{ab}	0.27	3.87^{a}	2.01	1.25^{a}
WP	1.86^{b}	1.22^{ab}	0.76^{b}	1.52^{a}	0.57^{a}	0.12^{ab}	1.30^{a}	1.05^{a}	0.21	3.68^{a}	1.95	0.98^{ab}
WR	1.85^{b}	1.07^{b}	0.62^{b}	1.58^{a}	0.62^{a}	0.11^{b}	0.71^{c}	0.81^{b}	0.27	3.20^{b}	2.16	0.61^{b}
Residue management practices												
BC	2.42^{a}	1.38^{a}	1.01^{a}	1.36	0.38^{b}	0.15^{ab}	1.38^{a}	1.93^{a}	0.18	4.56^{a}	2.96^{a}	1.07
CRI	2.25^{a}	1.33^{a}	0.86^{ab}	1.37	0.38^{b}	0.16^{a}	1.01^{b}	0.96^{b}	0.20	4.00^{b}	2.13^{b}	0.99
CRB	1.86^{b}	1.07^{b}	0.77^{bc}	1.52	0.57^{a}	0.11^{a}	0.73^{c}	0.55^{c}	0.20	3.02^{c}	1.61^{c}	0.92
CRR	1.36^{c}	0.99^{b}	0.66^{c}	1.58	0.68^{a}	0.11^{a}	1.03^{b}	0.36^{c}	0.28	2.73^{d}	1.47^{c}	0.80
Cropping systems	Microaggregates											
WM	1.52^{a}	0.72	0.87^{a}	0.99^{b}	0.20^{b}	0.23^{b}	0.91^{b}	1.95^{a}	0.43ab	2.52	2.24	0.69
WP	1.15^{b}	0.74	0.68^{b}	1.56^{a}	0.53^{ab}	0.17^{B}	1.10^{a}	1.58^{b}	0.25b	2.55	2.21	0.36
WR	1.07^{b}	0.68	0.64^{b}	1.83^{a}	0.67^{a}	0.48^{a}	0.47^{C}	1.29^{c}	0.72a	2.19	1.61	0.69
Residue management practices												
BC	1.59^{a}	0.74	0.81^{ab}	1.46	0.30^{b}	0.35^{a}	1.07^{a}	2.24^{a}	0.48^{a}	3.34^{a}	2.49^{a}	0.48
CRI	1.48^{ab}	0.73	0.85^{a}	1.38	0.37^{b}	0.16^{b}	0.82^{b}	1.44^{b}	0.65^{a}	2.66^{ab}	1.95^{b}	0.65
CRB	1.29^{b}	0.74	0.57^{c}	1.39	0.54^{a}	0.37^{a}	0.50^{c}	1.44^{b}	0.26^{b}	1.85^{b}	1.94^{b}	0.72
CRR	0.64^{c}	0.63	0.71^{b}	1.61	0.66^{a}	0.30^{ab}	0.91^{ab}	1.30^{b}	0.47^{a}	1.84^{b}	1.71^{b}	0.47

Very labile OC; VLC, labile OC; LC, less labile OC; LLC, non-labile OC; NLC, WM: wheat–maize; WP: Wheat–pearl millet; WR: Wheat–rice; BC: Biochar; CRI: Crop residue incorporation; CRB: Crop residue burning; CRR: Crop residue removal. The presence of identical letters within each column indicates that, based on the least significant difference test, there are no significant differences among the treatments (p<0.05)

results were consistent with Purakayastha et al. (2008), who demonstrated long-term benefits of organic residue incorporation on SOC fractions in a Typic Haplustept. The slow decomposition of lignocellulosic materials from root biomass and added organic residues (Nichols and Wright, 2006) contributed significantly to POM-C accumulation. These organic residues, by promoting soil aggregation, protect POM-C from rapid turnover. This study highlighted that BC and CRI treatments could enhance both the availability of labile organic materials and the stability of SOC within the soil. Such practices improved the physical structure of the soil and contributed to higher SOC sequestration, promoting microbial activity and nutrient cycling. In contrast, CRB and CRR resulted in lower SOC stability, indicating the unsuitability of these methods for long-term C management in intensive cropping systems.

3.3. Variation in total SOC pools with oxidizable organic carbon (OOC) fractions

In our study, when oxidizable organic carbon (OOC) fractions were analysed to assess the distribution of C with varying degrees of stability, we observed that RMPs affected the proportion of labile and recalcitrant C pools. The data showed that the OOC fractions, namely VLC (pool I), LC (pool II), LLC (pool III), and NLC (pool IV), were significantly influenced by 10 years of RMPs in wheat based cropping systems. Plots under WM cropping systems showed notably higher content of VLC of macroaggregates at all soil depths. Interestingly, Plots under WP and WR exhibited notably higher content of LC of macroaggregates compared to WM at soil depths of 0–15 cm and 15–30 cm (Table 3). Conversely, the WP plots recorded LCC content in macroaggregates in 0–15 cm and 15–30 cm soil depths. In the main plots, the recalcitrant pools of macroaggregates at 30–60 cm and 15–30 cm soil depths did not show any significant differences. Nevertheless, at a soil depth of 0–15 cm, the macroaggregate proportion was significantly higher in WM and WP than in WR cropping systems (Table 4).

Among the residue treatment plots, SOC fractions in macroaggregates of VLC were significant in case of BC and CRI plots compared to CRB and CRR plots in 0–15 cm and 15–30 cm soil depths. While considering the concentration of macroaggregates in recalcitrant pools at soil depths of 0–15 cm and 15–30 cm, the order was as follows: BC > CRI > CRB > CRR (Table 4). However, no observable difference was noticed in macroaggregate contents of LC (at 0–15 cm) and of recalcitrant pools (30–60 cm). Among the cropping system practices WM plots had the highest VLC content in 0–15 cm and 30–60 cm soil depths, while WR plots had the highest LC in microaggregates. However, the LLC content distributed in archaic manner in cropping system treated plots. In the 0–15 cm and 15–30 cm depth, microaggregate NLC was considerably higher both in cropping systems as well as residue treated plots than that of other fractions. Among the RMPs, the treatment of BC had the higher values of LLC fractions in all soil depths, while the highest value 3.34 g kg^{-1} and 2.49 g kg^{-1} non-labile C in the 0–15 and 15–30 cm soil depth, respectively (Table 4). So, the quantity of recalcitrant pools (pool III+pool IV) in microaggregates is considerably impacted by the 10-year application of BC as residue in 0–15 cm soil depth.

The WM plots consistently showed higher contents of VLC (pool I) in macroaggregates at all soil depths, reinforcing the positive role of residue management in promoting easily available C for microbial utilization. By bolstering crop productivities and promoting the production of crop residues (stubble, root biomass, and rhizodeposition) in the soil, long-term RMPs resulted in an increase in the labile SOC content. The substantial accumulation of organic manures, stubble, root biomass, rhizodeposition, and manure likely contributed to the enhancement of both total and labile SOC contents, as observed in studies by Ghosh et al. (2012) and Das et al. (2013). On the other hand, WP and WR plots exhibited higher contents of labile pools SOC in macroaggregates, suggesting that these treatments might favour C availability for short-term microbial processes. In the deeper soil layers (30–60 cm), no significant differences in the recalcitrant pools within macroaggregates were observed. This indicates that these fractions are less influenced by RMPs and cropping systems in the subsurface layers. Comparing the residue management treatments, BC and CRI plots consistently displayed higher contents of VLC (pool I) in macroaggregates at the topsoil and subsurface layers. These results demonstrate the efficacy of BC and CRI in promoting the availability of highly labile C for microbial consumption and nutrient cycling. The findings also showed that the contents of recalcitrant pools (pool III+pool IV) in macroaggregates was highest in BC–treated plots at 0–15 cm and 15–30 cm soil depths. This suggested long-term use of BC as a RMP significantly impacted the quantity of recalcitrant C pools, which were highly resistant to decomposition and crucial for long-term C sequestration. This resistance migh be associated with the biochemical properties of organic compounds present in organic manure or plant materials, as supported by studies conducted by McLauchlan et al. (2006) and Yan et al. (2012). In the current study, recalcitrant C showed a substantial increase compared to labile C. This phenomenon could be attributed to two factors: the preferential decomposition of labile compounds and the gradual accumulation of recalcitrant materials over time, as demonstrated by Lopez-Capel et al. (2008). Additionally, the increase in organic inputs also contributed to this outcome.

4. CONCLUSION

The long-term application of BC and CRI significantly improved SOC stability and increased labile C availability, making these practices more sustainable for wheat based cropping systems in north-western India. Biochar enhanced the recalcitrant SOC pools, supporting long-term C sequestration and climate change mitigation.

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