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Influence of crop residue management on soil carbon fractions, microbial activity and carbon sequestration: A review

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Abstract
Crop residues are an important source of organic carbon and nutrients in agricultural soils, yet they are often removed, burned or used for competing purposes. Their management can influence the amount of carbon entering the soil, the rate at which that carbon is decomposed, microbial activity and the formation of more persistent soil organic matter. This review synthesizes research on how residue retention, incorporation, removal and burning affect soil organic carbon (SOC), its labile and relatively stable fractions, microbial biomass and activity, and the potential for carbon sequestration. Evidence indicates that residue retention commonly improves surface SOC, particulate organic carbon, microbial biomass carbon and enzyme activity, especially when combined with reduced or zero tillage and balanced nutrient management. However, responses are not uniform. Residue quality, carbon-to-nitrogen ratio, soil texture and mineralogy, moisture and temperature regimes, crop rotation, duration of management and sampling depth all influence the outcome. Residue inputs can increase the amount of carbon mineralized during incubation while also increasing total SOC; therefore, greater CO_2 release from residue-amended soil does not necessarily mean that the system has lower long-term sequestration potential. Current understanding also emphasizes that soil organic matter is not a single homogeneous pool: particulate organic matter often responds relatively quickly to management, whereas mineral-associated organic matter is influenced by microbial transformation and the capacity of soil minerals to protect organic compounds. The review highlights the need for long-term, depth-resolved field experiments, consistent fractionation methods, carbon-budget approaches and practical residue-management strategies that account for livestock feed, soil cover, nutrient cycling and farm economics. Crop residues are most likely to contribute to durable soil carbon gains when they are managed as part of an integrated system rather than as an isolated input.

Keywords: Crop residue retention, soil organic carbon, carbon fractions, microbial biomass, carbon mineralization, conservation agriculture, carbon sequestration

Introduction

Soil organic carbon (SOC) is central to soil functioning because it supports nutrient cycling, aggregation, water retention and biological activity (Lal 2004) [1]. Agricultural management affects SOC by changing the balance between carbon inputs from crop residues and roots and carbon losses through decomposition, erosion and, in some settings, dissolved-carbon transport. Repeated residue removal and intensive soil disturbance can reduce organic inputs and expose previously protected organic matter to microbial decomposition. Conversely, retaining residues can return carbon to the soil, protect the surface from erosion and moderate soil temperature and moisture. These benefits are among the reason's residue retention is a key component of conservation agriculture (Paustian *et al.*, 2016) [2].

Residue management is not a simple choice between adding or removing plant material. Crop residues vary in lignin, soluble compounds, nitrogen content and C:N ratio, and these characteristics affect how rapidly they decompose and how nutrients are released. Their effect also depends on whether residues remain on the surface or are incorporated, the tillage system, rainfall pattern, soil texture and the crop sequence. A residue treatment that performs well in a cool, moist environment may behave differently in a hot, dry region where decomposition is restricted for much of the year (Palm *et al.*, 2001) [3].

Another important distinction is between carbon turnover and carbon storage. Microorganisms decompose plant material and release part of its carbon as CO_2, but they also convert some of it into microbial products that may become associated with mineral surfaces or protected within soil aggregates. Thus, carbon mineralization and carbon sequestration are linked processes rather than opposites (He *et al.*, 2023) [4]. Global syntheses report that residue retention and reduced tillage often increase SOC stocks, while the size and direction of changes in mineralizable carbon depend on soil and management conditions (Haddaway *et al.*, 2017) [5]; Bohoussou *et al.*, 2022) [6].

This review examines the influence of crop residue management on (i) SOC stocks and fractions, (ii) microbial biomass and enzyme activity, (iii) carbon mineralization and stabilization, and (iv) the practical conditions under which residue-based management can contribute to soil carbon sequestration. Particular attention is given to rainfed and semi-arid systems, where moisture limitation, residue scarcity and competing uses make management decisions especially context-specific.

Crop residues as a source of soil carbon

1. Quantity, placement and continuity of residue inputs

Residues supply organic carbon directly to the soil surface or, after incorporation, to the soil matrix. Their contribution is not limited to the visible straw left after harvest: roots, rhizodeposition and below-ground residues also supply carbon and may be distributed more deeply than surface straw. In many cropping systems, however, above-ground residues are the most manageable source of additional organic inputs (Hobbs *et al.,* 2008) [7]. Maintaining a reasonably continuous residue cover can reduce raindrop impact, slow runoff, limit erosion and buffer soil temperature. These physical effects can indirectly support carbon retention by protecting the soil surface and sustaining plant growth (Ranaivoson *et al.,* 2017) [8].

The quantity retained matters, but the relationship is not always linear. A larger residue input can raise microbial activity and CO_2 production in the short term, while the remaining carbon and microbial products may contribute to SOC over longer periods. Long-term gains depend on how much residue carbon enters the soil, how much is respired, and how much becomes physically or chemically protected. A carbon balance should therefore consider residue inputs, root-derived carbon, crop productivity, erosion and changes in SOC stocks rather than relying on a single measurement of respiration or SOC concentration (Kuzyakov 2010) [9].

2. Residue quality and the C:N ratio

Residues differ in decomposability. Material rich in soluble carbohydrates and nitrogen is generally decomposed more rapidly than material with high lignin content or a wide C:N ratio. Cereal straws often contain relatively little nitrogen and can temporarily immobilize mineral nitrogen as microbes use available nitrogen to decompose the carbon-rich material. Legume residues generally have a narrower C:N ratio and can decompose more rapidly, although their actual behavior depends on maturity, chemical composition and local conditions. Combining residue retention with an appropriate nutrient supply can help avoid severe nutrient immobilization and support microbial processing (Burns *et al.,* 2013) [10].

Rapid decomposition should not automatically be interpreted as poor carbon management. Microbes can convert relatively labile compounds into microbial biomass and residues, some of which may later associate with minerals. The microbial efficiency-matrix stabilization framework explains why plant inputs that are readily used by microorganisms can contribute to stable soil organic matter when microbial products interact with the soil matrix (Cotrufo *et al.,* 2019) [11].

Effects of residue management on soil organic carbon and its fractions

1. Total soil organic carbon and carbon stocks

Residue retention is commonly associated with higher SOC than residue removal or burning, particularly when it is maintained for several years and combined with reduced soil disturbance. A global meta-analysis based on 243 studies reported increases in SOC stock under no-tillage and reduced tillage, with larger average gains when residue retention was included (Haddaway *et al.,* 2017) [5]. Another global synthesis found that conservation-agriculture components, including permanent soil cover, increased SOC and total nitrogen stocks, with effects most apparent in surface soil (Bohoussou *et al.,* 2022) [6].

Surface accumulation is a recurring feature of no-tillage and residue-retention systems because residues remain near the soil surface and mixing is limited. Consequently, results can depend strongly on sampling depth. A higher SOC concentration in the upper few centimeters does not necessarily mean that the whole soil profile has gained an equivalent amount of carbon (Powlson *et al.,* 2014) [12]. Comparing systems requires consistent depth intervals and, where bulk density differs, stock calculations that account for soil mass or equivalent soil mass. Long-term experiments and profile sampling are essential to distinguish redistribution from net sequestration Luo *et al.,* 2010) [13].

2. Labile carbon pools

Labile or relatively active carbon fractions respond more quickly to changes in organic inputs and microbial activity than bulk SOC. Depending on the analytical method, these may include permanganate-oxidizable carbon, water-extractable organic carbon, particulate organic carbon and other operationally defined fractions. Residue retention can increase these pools because fresh plant material and partially decomposed fragments enter the soil (Tigga *et al.,* 2020) [14].

An increase in labile carbon can indicate improved carbon supply and biological activity, yet it may also indicate a pool that is more readily decomposed. For this reason, a larger labile fraction is not by itself proof of long-term sequestration. Its interpretation is stronger when considered alongside total SOC, microbial biomass, aggregate stability, mineral-associated carbon and repeated measurements over time. Residue management should be evaluated in terms of both the size of responsive pools and the pathways through which carbon may be transferred into more persistent forms (King *et al.,* 2024) [15].

3. Particulate organic carbon and mineral-associated organic carbon

Recent soil-organic-matter frameworks distinguish particulate organic matter (POM) from mineral-associated organic matter (MAOM). POM includes relatively recognizable plant fragments and partially decomposed material; it often responds rapidly to changes in residue inputs and can be sensitive to disturbance. MAOM consists of organic compounds associated with mineral surfaces and is often more persistent, although its stability is not absolute and depends on environmental conditions. The two pools differ in formation pathways, turnover and response to management (Cotrufo *et al.,* 2022) [16].

Residue retention can increase POM by supplying fresh plant material. Whether it also increases MAOM depends on microbial transformation, mineral surface availability, soil texture and mineralogy, pH, nutrient status and time. Microbial processing can produce compounds that bind to mineral surfaces, while aggregation can physically protect organic matter. Thus, management that increases residue input may not produce the same proportional change in POM and MAOM. Soils with limited mineral protection capacity may accumulate more particulate material than mineral-associated carbon, while carbon-poor soils with available mineral surfaces may have greater potential for MAOM formation (Lavallee *et al.,* 2020) [17].

4. Aggregate-associated carbon and physical protection

Soil aggregates can protect organic matter by limiting access to substrates and modifying the movement of oxygen, water and enzymes. Residue cover and reduced tillage can promote aggregation through lower mechanical disruption, greater root growth and increased fungal activity. Organic binding agents produced by roots and microorganisms, including fungal hyphae and extracellular compounds, may contribute to aggregate formation. The extent of protection depends on texture, wetting and drying, tillage intensity and the stability of aggregates under field conditions (Chen *et al.,* 2020) [18].

Glomalin-related soil protein (GRSP) measurements are used to investigate links among arbuscular mycorrhizal fungi, aggregation and SOC. GRSP-related indicators can be informative when interpreted cautiously and combined with independent measures of fungal abundance, aggregate stability and SOC (Wright *et al.,* 1998) [19].

Influence on microbial biomass and activity

1. Microbial biomass carbon and nitrogen

Crop residues supply energy and nutrients to soil microorganisms. Where residues are retained and soil moisture is adequate, microbial biomass carbon (MBC), microbial biomass nitrogen and microbial quotient may increase. A global meta-analysis of conservation-agriculture studies reported higher microbial biomass under no-tillage with residue retention than under conventional tillage without retention (Zuber and Villamil 2016) [20]. Long-term experiments in India have likewise found positive effects of conservation tillage on SOC and selected microbial indicators, although the magnitude of the response depends on crop rotation, duration and soil conditions (Yadav *et al.,* 2020) [21]; (Pratibha *et al.,* 2023) [22].

MBC represents the living microbial pool at the time of sampling; it is not equivalent to the amount of carbon that will become stable SOC. Microbial biomass can rise quickly after residue addition and decline as the substrate is consumed or the soil dries. Sampling season, recent rainfall, crop stage, soil depth and laboratory handling can therefore influence results. The microbial quotient (MBC as a proportion of SOC) may provide additional information about how much of the organic-carbon pool is held in living microorganisms, but it should be interpreted together with absolute MBC and SOC values (Sun *et al.,* 2020) [23].

2. Soil enzyme activity and nutrient cycling

Enzymes such as dehydrogenase, β-glucosidase, urease, phosphatase and cellulase-related activities are often measured to describe microbial functioning and nutrient cycling. Residue inputs can increase enzyme activity by providing substrates and supporting a larger or more active microbial community (Tiwari *et al.,* 2019) [24]. Yet individual enzymes respond differently: their activity depends on the substrate, nutrient limitation, soil pH, temperature and moisture, as well as microbial community composition. Higher enzyme activity may indicate more active decomposition and nutrient release, but it does not necessarily indicate lower or higher long-term SOC storage on its own (Fanin *et al.,* 2022) [25].

Residue quality can shape the timing of these responses. Easily decomposable residues may stimulate rapid microbial growth, while high-C:N residues can temporarily increase microbial demand for nitrogen. Integrated nutrient management may help maintain decomposition and crop growth without excessive nutrient limitation. In rainfed systems, residue cover can also conserve soil moisture and moderate temperature, indirectly extending periods during which microbes and roots remain active (Cao *et al.,* 2021) [26].

3. Microbial community structure and functional responses

Residue management can alter microbial community composition by changing substrate supply, soil moisture, aeration and disturbance. Bacteria and fungi contribute to different aspects of decomposition, although their roles overlap and should not be reduced to a simple bacteria-versus-fungi distinction. Fungal hyphae can contribute to soil aggregation, while bacterial communities play important roles in nutrient transformations and the processing of soluble compounds. Long-term conservation-agriculture research under semi-arid rainfed conditions in India has documented management-related differences in bacterial community structure, enzyme activities and soil properties (Pratibha *et al.,* 2023) [22].

Microbial diversity metrics alone do not reveal the direction of carbon storage. A community can be diverse yet experience rapid carbon turnover, or it can efficiently convert inputs into microbial products under suitable conditions. Future studies should connect community data with measured carbon fluxes, microbial carbon-use efficiency, enzyme activity, residue chemistry and changes in SOC fractions. This would help explain not only which organisms are present, but also what they are doing in the carbon cycle (Nielsen *et al.,* 2011) [27].

Carbon mineralization: decomposition and sequestration are connected

Carbon mineralization is the microbial conversion of organic carbon into inorganic forms, principally CO_2 under aerobic conditions. Laboratory incubation studies commonly estimate mineralization by measuring CO_2 released from soil over time. Residue addition can increase cumulative CO_2-C because it supplies decomposable substrate. This response is expected and does not by itself demonstrate that residue management is failing to sequester carbon. The key question is how the additional carbon input compares with respiratory losses and other pathways of carbon removal, and how much carbon remains in soil pools after a sufficiently long period (Schaedel *et al.,* 2019) [28].

A global meta-analysis of 132 papers found that no-tillage and residue retention generally increased absolute mineralizable carbon, while responses in mineralizable carbon relative to SOC were more variable and depended on conditions such as soil pH, texture, duration and nitrogen input (He *et al.,* 2023) [4]. This distinction is important. Absolute mineralizable carbon describes the size of the pool that can be mineralized under the incubation conditions; specific mineralizable carbon describes mineralization relative to the SOC present. A soil with more SOC can release more CO_2 during incubation while having a smaller mineralizable proportion of its total SOC.

Residue quality, temperature and moisture strongly regulate mineralization. Warm, moist and well-aerated conditions usually support faster decomposition than cold or dry conditions, although waterlogging can shift microbial

pathways and increase the importance of anaerobic processes. Fine-textured soils may protect organic matter through aggregation and mineral association, but texture alone cannot predict the outcome because mineralogy and soil structure also matter. Rewetting after a dry period can produce a short-lived pulse of CO_2 as microorganisms respond to newly available substrates. Incubation results should therefore be interpreted in relation to the conditions under which samples were collected and incubated (Jia *et al.,* 2020) [29].

Field carbon sequestration cannot be inferred from incubation CO_2 alone. A robust assessment should combine changes in SOC stocks, residue and root inputs, crop yields, erosion risk and, where relevant, greenhouse-gas emissions from the whole production system (Conant *et al.,* 2011) [30]. It should also distinguish carbon concentration from stock and consider equivalent soil mass where bulk density differs. These measures are particularly important in conservation-agriculture systems, where carbon may accumulate near the surface while deeper layers respond differently (Fowler *et al.,* 2023) [31].

Residue management options and their trade-offs

1. Surface retention under reduced or zero tillage

Surface residue retention under reduced or zero tillage can protect soil from raindrop impact, reduce evaporation and temperature extremes, support soil organisms and limit the physical disruption of aggregates. Global syntheses indicate that combining residue retention with minimum tillage often improves SOC stocks more consistently than relying on tillage reduction alone. Benefits may be especially useful in rainfed systems, where conserving water between rainfall events can improve crop establishment and reduce the risk of soil erosion (Xiao *et al.,* 2021) [32].

Nevertheless, residue retention can complicate seeding operations, affect weed management, alter soil temperature during early crop growth and create temporary nitrogen immobilization. The magnitude of these trade-offs depends on residue load, machinery, crop calendar, soil moisture and local pest pressure. Recommendations should be based on the cropping system and should avoid presenting zero tillage as a stand-alone solution when crop diversification, nutrient management and residue supply are inadequate (Thierfelder *et al.,* 2018) [33].

2. Incorporation of residues

Incorporation places residue in closer contact with soil microorganisms and can accelerate decomposition by improving contact with moist soil. It may provide nutrients more rapidly, but tillage also disrupts aggregates and can increase aeration and exposure of protected organic matter. The net effect on SOC depends on the balance between new residue inputs, decomposition and physical protection. In some systems, partial incorporation or strategic placement may be useful, but the outcome should be evaluated against the benefits of surface cover and reduced disturbance (Datta *et al.,* 2019) [34].

3. Residue removal and burning

Residue removal may be necessary where straw is used as animal feed, bedding, fuel or a raw material for other products. However, removing most above-ground residues reduces the carbon and nutrient return to soil and may leave the surface more exposed to erosion and moisture loss. Burning rapidly converts much of the residue carbon to gases and particulate emissions, while some mineral nutrients remain in ash and others are lost. Burning also removes protective cover at a time when soil may be vulnerable to wind or rainfall. Where complete retention is not feasible, partial retention, manure return, composting or other locally appropriate organic amendments can help maintain soil carbon inputs (Alvarez *et al.,* 2024) [35].

In India, residue-management decisions are shaped by competing demands for fodder, the cost of collection and transport, farm size, availability of seeders and residue-handling equipment, and the timing between crops. A practical recommendation must account for these constraints rather than assuming that all residues can remain in the field. Efficient residue use therefore includes avoiding open burning, retaining a feasible fraction for soil cover, and returning processed organic materials where agronomically and economically appropriate (Kumar *et al.,* 2023) [36].

Implications for rainfed and semi-arid cropping systems

In rainfed regions, residue retention can have a value beyond carbon storage because it reduces direct evaporation and moderates soil temperature. These effects may improve water-use efficiency and help stabilize crop production during periods of irregular rainfall. At the same time, dry conditions can slow decomposition and microbial activity, so carbon turnover may occur in pulses after rainfall. Residue management must therefore be adapted to the local rainfall regime, residue production, soil texture and cropping sequence (Padbhushan *et al.,* 2024) [37].

Long-term semi-arid experiments are particularly valuable because the same residue treatment can produce different responses across years with contrasting rainfall. Studies in rainfed pigeonpea–castor systems at ICAR-CRIDA have examined tillage and residue levels in relation to soil bacterial communities, enzyme activity, nutrients and greenhouse-gas emissions, illustrating the value of integrating biological and biogeochemical measurements. Such experiments can help clarify whether observed changes in microbial indicators are accompanied by sustained changes in carbon stocks (Aditi *et al.,* 2022) [38].

For dryland agriculture, the most useful strategy is usually an integrated one: maintain as much residue cover as is feasible, minimize unnecessary disturbance, diversify crops where possible, and match nutrient inputs to residue quality and crop demand. Where residue supply is low, cover crops, legume rotations, manure or compost may complement residue retention, subject to water availability and local resource constraints. Carbon benefits should be measured over multiple years because single-season responses can be dominated by weather and short-term decomposition (Plaza-Bonilla *et al.,* 2015) [39].

Research gaps and future directions

- Long-term and depth-resolved measurements: Studies should measure SOC stocks through the soil profile and report bulk density, sampling depth and equivalent-soil-mass procedures where appropriate.
- Better separation of carbon pools: Research should combine total SOC with POM/MAOM, particulate organic carbon, mineral-associated carbon and selected labile fractions, while clearly reporting extraction methods.

- Linking biology to carbon outcomes: MBC, microbial quotient, enzyme activities, microbial community structure and fungal indicators should be related to measured carbon fluxes and changes in carbon fractions.
- Improved mineralization protocols: Incubation studies should report temperature, moisture, duration, pre-incubation, residue additions and whether results are expressed as absolute or SOC-normalized mineralization.
- Residue quality and nutrient interactions: More studies are needed on the combined influence of C:N ratio, lignin, nutrient supply, residue placement and crop rotation, especially in rainfed systems.
- Whole-system carbon accounting: Carbon gains should be considered alongside crop productivity, fuel use, residue transport, erosion, greenhouse-gas emissions and the alternative uses of residues.
- Farmer-centred evaluation: Research should assess machinery needs, labour, fodder competition, economics and the amount of residue that can realistically be retained without compromising household and livestock needs.

Conclusion

Crop residue management can improve soil carbon status by increasing organic inputs, protecting the soil surface and supporting microbial processes involved in carbon transformation. Residue retention, particularly when combined with reduced soil disturbance and suitable nutrient management, often increases SOC and microbial biomass in the surface soil. However, changes in individual carbon fractions and mineralization rates are not uniform. Labile and particulate pools may respond quickly, whereas mineral-associated carbon depends on microbial transformation and the protective capacity of soil minerals. Greater CO_2 release during decomposition is not, by itself, evidence of lower carbon sequestration; it must be interpreted against total carbon inputs and changes in soil stocks. For rainfed agriculture, residue management should be adapted to local soil, climate, crop sequence and competing uses. Progress will depend on long-term field experiments, consistent carbon-fraction measurements and integrated carbon budgets that connect soil biology with measurable changes in carbon storage.

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