

Soil carbon fractions and their role in climate-resilient agriculture: A review

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ABSTRACT

Soil, a complex and dynamic ecosystem, is a vital support system for life on Earth. Soil carbon fractions—from transient, labile forms to persistent recalcitrant pools—play a key role in climate mitigation, soil fertility, and sustainable land management. This review synthesizes current knowledge on soil organic and inorganic carbon fractions' behavior, stability, and ecosystem functioning across climatic gradients and land use types. We evaluate their differential responses to environmental stress and human-induced disturbances, emphasizing their contributions to greenhouse gas dynamics, nutrient cycling, and soil structure. Fraction targeted analysis propose strategic interventions for enhancing soil carbon sequestration and climate resilience in agricultural systems. By realigning/refocusing carbon management around fraction-specific functionality, this review offers a conceptual framework for utilizing soil carbon in environmental and agronomic climate-smart agriculture strategies. This review highlights the relevance of soil carbon fraction management in advancing climate-resilient practices (SDG 13), enhancing sustainable agricultural productivity (SDG 2), and fostering ecosystem restoration and land sustainability (SDG 15).

1. Introduction

Soils constitute Earth's largest terrestrial carbon reservoir, storing more carbon than the atmosphere and biosphere combined. This capacity, however, is governed not just by the total carbon content but by the nature and dynamics of distinct soil carbon fractions. From labile pools that turnover within days to recalcitrant forms that persist for centuries, each fraction of soil organic carbon (SOC) plays a functional role in determining how soils respond to climate change and agricultural practices [1]. In order to better model the contributions of particular fractions, such as dissolved organic carbon (DOC), mineral-associated organic carbon (MAOC), and microbial biomass carbon (MBC), to nutrient cycling, greenhouse gas (GHGs) regulation, and long-term carbon stabilization, there has been an increase in interest over recent years [2]. MBC represents the living fraction of SOC, important for nutrient cycling and a sensitive indicator of management effects. DOC is the most mobile pool, serving as an immediate microbial energy source and facilitating carbon transfer. Light fraction organic carbon (LFOC), composed of partially decomposed residues, has rapid turnover and is an early indicator of land-use changes. Particulate organic carbon (POC),

linked with soil aggregates is highly responsive to tillage and residue management, also acting as a nutrient reservoir. In contrast, MAOC forms stable organo-mineral complexes with clay and silt, ensuring long-term carbon storage and resistance to decomposition [3].

Soil inorganic carbon (SIC), composed mainly of carbonates, is categorized into geogenic (formed during soil parent material weathering) and pedogenic carbonates (secondary carbonates precipitated within the soil), and is especially significant in arid and semi-arid environment where it can constitute over 90 % of total soil carbon stocks [4]. (Fig. 1). Complex interaction between physical, chemical, and biological processes controls these carbon fractions, which vary in stability and turnover rates. Labile fractions such as DOC and POC are highly dynamic and responsive to environmental stimuli, acting as short-term indicators of soil health and fertility [5,6]. In contrast, MAOC and SIC serve as long-term carbon sinks, contributing to sustained sequestration and climate resilience through mineral binding and precipitation pathways [7,8]. The stability and function of these fractions are further regulated by soil pH, texture, microbial activity, and climate. Microbes have a critical role in converting organic residues into stable forms of SOC and accelerating SIC precipitation. For example, microbial

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respiration regulates CO₂ dynamics in the soil, affecting both SOC formation and carbonate dissolution [9,10].

The largest terrestrial carbon store is found in the top meter of the world's soil, which contains about 2200 Pg (Petagram = 10¹⁵ g = billion metric ton) of soil carbon, of which 1500 Pg is SOC. Comparatively, the estimated value of SIC ranges from 700 to over 1000 Pg [11]. Soil carbon pool is estimated to be 3.2 times larger than the atmospheric pool (800 Gt) and nearly five times greater than the biotic pool of plants and animals (560 Gt) [12]. The precipitation of SIC mostly happens in the deeper soil profile, in contrast to SOC, which builds up in the topsoil [8]. The SOC pool contains 725 Pg of carbon in the soil's surface (0–30 cm) layer. SIC reserves are predicted to be around 950 Pg carbon in the first-meter depth, whereas SIC and SOC pools are equivalent to 1500 Pg in the second-meter depth [9,13]. The low organic carbon content of Indian soils, which averages 3.2 g kg⁻¹, can be attributed to the country's unique geographical and climatic factors, such as dry land cultivation (69 %) and extensive topsoil erosion [14]. According to Sreenivas et al. (2016), the estimated soil carbon stocks in India's top one meter amount to approximately 22.72 Gt of SOC, 12.83 Gt of SIC, and a total of 35.55 Gt of soil carbon [15]. Divergent forecasts of carbon stock for Indian soils range from 6.5–8.5 Gt to 20.5–23.4 Gt [16]. As a result, India's role in the global SOC reservoir is projected to be in a spectrum of 20–25 Gt for the top 1 m. Given the Indian subcontinent's annual carbon emissions of roughly 566 million tonnes, there is an urgent need to maintain carbon sequestration rate in India from 23–28 per mile, as opposed to the worldwide requirement of 4 per mile [17]. Long-term studies have conclusively shown that, in various agricultural ecological zones across the nation, depending mainly on the aridity index of the site, soils must receive at least 0.31 to 5.16 t C ha⁻¹ yr⁻¹ via stubble or other organic sources to efficiently manage and sustain the SOC level [8]. In the Central Himalayas of India, Kaushal and Baishya (2024) investigated SOC and SIC dynamics over a 3000 m elevation gradient and eight different forest types [18]. They found that SIC accounts for up to 31 % of total soil carbon, an overlooked component. SOC and SIC fluxes were 4.63 and 1.68 Mg C ha⁻¹ yr⁻¹ respectively, with higher SOC near the surface and variable SIC trends. Soil pH, soil organic matter (SOM), and climate emerged as key drivers of carbon stocks, highlighting the need for SOC restoration in India's generally low-carbon and less fertile soils.

Modifications in land management and land use have significantly influenced soil carbon levels, the earth's most significant terrestrial carbon reservoir [19]. For instance, since the beginning of agriculture, the turning of non-cultivated land has resulted in a detriment of around 5 % of the world's terrestrial carbon supply or a decline of ~116 Pg in global carbon stocks [20]. Farming approaches that increase carbon in the soil can remove CO₂ from the atmosphere and keep it there, while

making crops grow better and soil nutrients cycle more efficiently. Agroforestry, the addition of organic matter, and changes in land use are management techniques that have been studied for their impact on soil carbon fractions [21]. The soil represents a substantial percentage of the carbon cycle, with estimates ranging from 2400 to 3600 Pg C, approximately two-thirds of the terrestrial carbon cycle [22]. The soil carbon cycle involves complex transformations and bidirectional flows of carbon among the pools that regulate the overall carbon cycle [23] (Fig. 2).

While total SOC and SIC have been widely assessed, fraction-specific approaches remain neglected in climate-smart agricultural models and land management strategies. A limited understanding persists regarding the individual contributions of specific carbon fractions to carbon sequestration, particularly under shifting climatic and land-use conditions. This review addresses this gap by systematically examining the behaviours of SOC and SIC fractions across diverse environmental gradients and management regimes, further exploring their critical roles in soil restoration and greenhouse gas mitigation. This review proposes a directional framework for integrating fraction-sensitive approaches into sustainable land use practices by highlighting advances in carbon modeling, microbial dynamics, and soil management strategies. Achieving the climate mitigation targets of the Paris Agreement and Sustainable Development Goal 13 (SDG 13) requires effective management of soil carbon fractions as a part of sustainable climate action. Enhancing the stability and functionality of specific soil carbon pools through targeted land management can meaningfully reduce atmospheric CO₂ concentrations, strengthen agroecosystem resilience, and accelerate the transition toward climate-neutral agriculture.

Existing models often underestimate the combined effects of climatic drivers (temperature, precipitation, moisture) and soil-specific factors (pH, texture, topography) on carbon sequestration, and the limited focus on SOC–SIC interactions further contributes to uncertainties in predicting sequestration potential. While several reviews have examined SOC in relation to climate change, most have addressed it in a generalized manner, focusing on global stocks, sequestration, or management strategies, without integrating the fraction-level dynamics or the dual roles of carbon pools in mitigation and adaptation. This review addresses this gap by integrating climatic and soil controls on both SOC and SIC fractions, offering a novel perspective to improve predictions and strengthen climate change mitigation strategies. Leveraging soil carbon management practices such as biochar application, conservation tillage, cover cropping, and organic amendments can enhance stabilization pathways across different carbon fractions, from labile to stable pools that provide long-term carbon storage. This review highlights the potential of soil carbon pools as scalable pathways for climate mitigation and sustainable land management, linking their dynamics to SDGs (2, 13, 15) while addressing gaps in previous climate-smart soil studies.

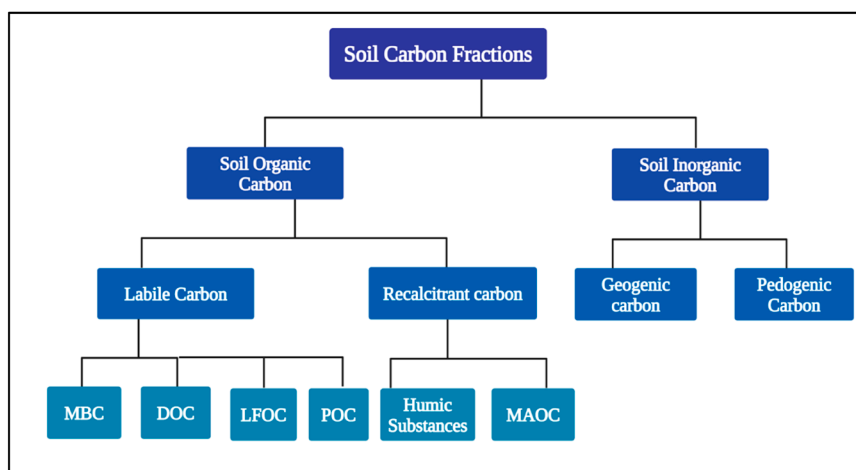


Fig. 1. Classification of soil carbon fractions.

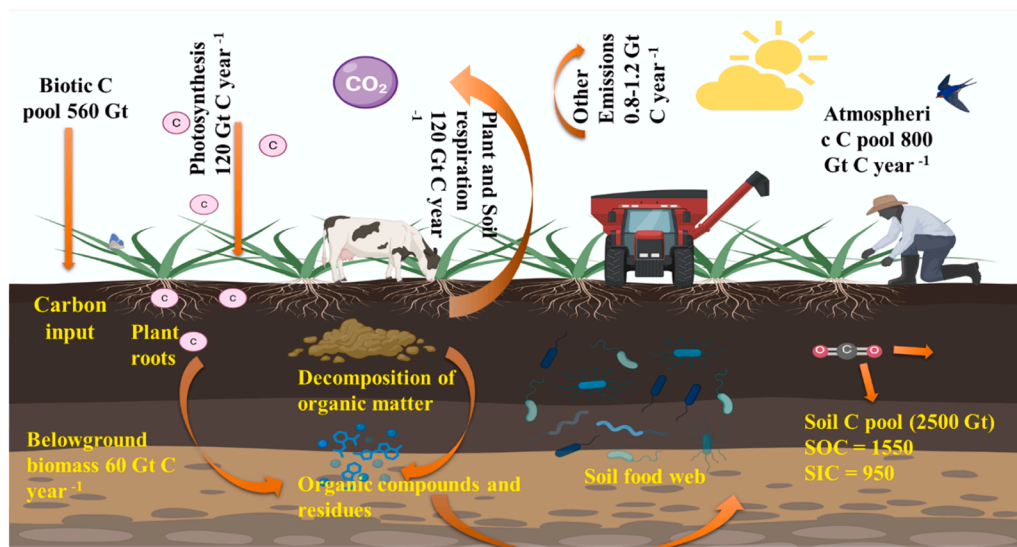


Fig. 2. Carbon balance in the soil is regulated by the carbon inputs derived from photosynthesis and the carbon losses resulting from respiration.

2. Classification of soil carbon fractions

2.1. Soil Organic carbon (SOC)

SOC is derived from biological sources such as plant litter, root exudates, and microbial residues. It can be broadly categorized into labile (short-lived, rapidly cycling) and recalcitrant (long-lived, stable) pools. These fractions influence nutrient cycling, microbial activity, and long-term soil fertility [24]. The worldwide stock of SOC, up to a depth of 2 m, is projected to be around 2400 Gt C. This is three times the amount of carbon in the atmosphere [25]. Therefore, small changes in SOC stocks can significantly impact climate change and atmospheric CO₂ levels [26, 27]. A specific aspect of the broader global carbon cycle is SOC, which includes carbon cycling via the atmosphere, vegetation, soil, and sea.

Bellè et al. (2022) studied SOC stocks and quality in small-scale tropical, subhumid, and semi-arid watersheds in southwest India [28]. It emphasizes the wide range of SOC stocks in the top 60 cm of soil, which range from 58.2 to 169.4 Mg C ha⁻¹ and are impacted by soil parameters, vegetation type, and geology. The study highlights the significance of subsurface contributions (up to 40 %) to overall SOC stocks and identifies essential causes, including vegetation history, land-use changes, and soil physico-chemical characteristics. Regression kriging and geostatistical modeling are used to evaluate the spatial heterogeneity of soil properties in the Himalayan district of Kishtwar. Nutrients, NDVI, pH, and OC are important soil characteristics that are examined. Spatial modeling revealed patterns influenced by topography and land-use practices. The fertility was considered moderate with an average OC of 1.19 % [29]. More precise field data are required to provide comprehensive information on SOC dynamics in tropical and ecologically sensitive ecosystems of India.

2.1.1. Labile organic carbon (LOC)

Water-soluble proteins, hemicelluloses, sugars, and other materials form the labile carbon pool. This pool is soluble in hot, cold, and salt-water solutions. Due to their elevated biological activity, LOC fractions are significant components in the carbon cycle and could be considered sensitive and early indicators of changes in SOC. Furthermore, variations in active SOC fractions can reflect cultivation and land use techniques, making them a crucial metric for evaluating the quality of SOC pools [30]. These fractions turnover rapidly (days to months), yet they play a key role in feeding microbial life, initiating humification, and supporting nutrient cycling [31,32]. Labile SOC fractions responded strongly to organic amendments, with organic fertilizer and straw

showing the greatest increases in MBC and microbial diversity while achieving the lowest GHG emissions per unit carbon input. These findings showed the important role of labile SOC fractions in enhancing carbon sequestration and sustaining soil health [33].

2.1.2. Microbial biomass carbon (MBC)

MBC is the carbon content of microorganisms living in the soil environment, such as microbes, actinomycetes, fungi, algae, protists, and other soil microfauna [34]. Soil bacteria are necessary to transform nutrients, cycling of organic matter, and macro aggregation to maintain adequate moisture and promote proper aeration. Bacterial richness increases from acidic to neutral pH levels, but shows a slight decrease under alkaline conditions [35]. In humid areas, microorganisms favouring acidic environment are more common, while in arid areas, those adapted to alkaline conditions dominate. Soil microbial communities are shaped by soil texture, second only to pH. While silt and clay fractions enhance filamentous bacteria and some fungi, coarse-textured soils increase the diversity of fungal species [36]. In Eastern Himalayan soils, Lepcha and Devi (2020) examined the effect of season, soil depth, and land-use type on the MBC [37]. The forest had the greatest annual mean MBC, followed by rice farmland and cardamom agroforestry. Cardamom agroforestry and forests have higher SOC content, which suggests that restoring the litter layer through retrogressive land-use change speeds up microbial carbon immobilization, which helps with soil fertility and carbon sequestration. MBC was at its lowest during the winter and highest during the rainy season. Similarly, in the temperate forest of Uttarakhand MBC ranged from 192 to 6210 µg/g, with peak values during the rainy season due to high moisture and organic matter content, and lowest in winter. MBC contributed approximately 6 % to total SOC. Changes in soil moisture and organic carbon significantly influence microbial carbon dynamics [38]. In contrast, Williams et al. (2025) conducted a meta-analysis of 1012 soils across diverse climates and found that soils in tropical and temperate regions with low OC (~7.8 g C/kg) had higher MBC than cold subalpine soils with high OC (~126.7 g C/kg), challenging the assumed direct OC-MBC link. The study identified that climate and soil texture affect microbial abundance [39].

2.1.3. Dissolved organic carbon (DOC)

DOC are small molecules formed from litter leachates, root exudates, and microbial metabolites that pass through 0.22–0.70 µm size filters. The DOC reservoir influences the balance of oceanic and atmospheric CO₂, potentially rendering it climatically crucial [40]. According to Guo

et al. (2020), DOC is the primary substrate for microorganisms that rapidly degrade in soils. The DOC concentration in soils is influenced by all factors involved in litter production, root growth, and microbial activity [41]. DOC concentration in top soils are primarily influenced by precipitation, soil classification, climate zones, and land cover types [42, 43]. Yu et al. (2024) conducted a 20-year study in a subtropical forest and found that most DOC came from the litter layer, while soils trapped it through absorption and microbial use. DOC decreased with depth due to retention in clay-rich, acidic soils. Over time, surface soils showed increasing DOC, due to cleaner air, more rainfall, and warmer temperatures. This shows the important role of soils in storing carbon and regulating its movement under changing environmental conditions [44].

2.1.4. Light fraction organic carbon (LFOC)

LFOC is the undecomposed or partially degraded organic matter that floats in dense solution extraction [32]. In agricultural soils, the fraction of LFOC in SOC ranged from 2–18 % [45]. The two components, LFOC and DOC, represent the primary undecomposed or partly degraded elements of dense SOM, which are influenced by the quantity of MBC and the components of microorganisms [46]. The main factors that affect LFOC are vegetation type and litterfall composition [47]. These fractions increase with vegetation restoration and decrease with soil depth [48]. Compared to the heavier fractions, LFOC is easily broken down and aids in the short-term turnover of carbon. This is because a large portion of LFOC, compared to LOC, comes from recently added organic matter that is either preserved or partially decomposed [49].

2.1.5. Particulate organic carbon (POC)

POC comprises plant residues, root fragments, and microbial biomass attached to soil aggregates [50]. POC is a percentage of organic carbon between more stable and labile forms. The amount of POC in SOC in agricultural soil range from 20–45 % [45]. POC is important for aggregate formation and is highly responsive to land use and temperature changes [51,52]. It contributes significantly to the agglomeration of soil and the incorporation of carbon derived from plants into clusters, suggesting that it may represent the early stages of MAOC [53]. It can, therefore, serve as a source of consistently available nutrients. High temperatures generally increase decomposition rates, leading to faster turnover of POC. High precipitation promotes plant growth and carbon inputs, which influence POC levels, along with greater net primary productivity (NPP), elevation, pH, clay plus silt content, and land cover [54]. A ¹³C-labeling experiment showed that up to 12.29 % of dissolved carbon was detected in the POC pool, enhancing soil carbon sequestration [55]. Rocci et al. (2021), in a meta-analysis of 98 studies, found that POC reacts more quickly to environmental changes than other soil carbon forms. POC increased with nitrogen fertilizer (+13.17 %) and elevated CO₂ (+5.11 %) because of higher plant litter but decreased under warming (−10.05 %) due to faster decomposition [56]. These results show that POC is a useful short-term indicator of soil carbon change and should be studied separately to understand carbon dynamics under climate and land use changes.

2.2. Recalcitrant Organic carbon (ROC)

Recalcitrant carbon includes long-lived organic compounds (thousands of years) contributing to stable soil carbon pools and long-term carbon sequestration [57]. Stable SOC fractions include MAOC and HS [58]. With succession age, the proportion of SOC fractions increased, particularly that of ROC, which constituted 62 % to 85 % of the total SOC. Research conducted by Lal et al. (2004) reveals that RC pools take a long time to break down. Hence, microorganisms cannot readily access them [59]. Any of the humic compounds can delineate the RCP. In a long-term field study conducted by Xiao et al. (2025) on paddy soils, ROC increased significantly under organic fertilizer, particularly during drying conditions, leading to increased microbial activity and methane

oxidizing bacteria, thus linking ROC to higher GHG emissions [33]. ROC pool often dominates in mature ecosystems and offers long-term storage, making them critical for climate mitigation goals [60].

2.2.1. Humic substances (HS)

These complex macromolecules (including humin, humic acid, and fulvic acid) resist microbial degradation due to aromatic ring structures. Humic compounds comprise 60–80 % of the TOC [61]. Nearly 70 % of the organic matter in the soil is composed of humus, an intricate blend of compounds containing carbon that can stay in the soil for several hundred years and has a color ranging from brown to black [62]. HS enhance soil structure, water retention, and also act as bio stimulants that promote root growth and plant stress tolerance [63]. HA are high molecular weight chemical compounds created during the breakdown of residual plant and microbial material. For maintaining nutrient level and preserving soil fertility, the reactive fraction of HS, HA, is essential in soil [64]. FA are smaller molecules that dissolve in water more efficiently than humic acids [65]. Instead of viewing soil organic matter as made up of fixed, chemically resistant humic compounds, recent research suggests it is better understood as a continuum of organic matter. Its stability in soils is shaped not so much by inherent resistance to decay, but by how organic matter interacts with minerals, becomes physically protected in soil pores, and is continually transformed by microbes [12]. A study by Spaccini et al. (2002) found that HS with higher hydrophobicity increase the sequestration of organic carbon in soil by protecting labile organic compounds from microbial decomposition [66]. According to Hayes and Swift (2020) high molecular weight humic acids enhance carbon sequestration by forming complexes with metals and minerals, reducing microbial degradation [67]. Xu et al. (2024) conducted a 16-year study on the Loess Plateau, found that alfalfa (*Medicago sativa* L.) revegetation enhanced SOC by 13.7 % through humic substances [68]. Alfalfa increased HA and humin within the heavy SOC fraction, supported by micro-aggregate formation. This accumulation of stable humic compounds leads to a long-term carbon stabilization and improved soil function in semi-arid regions.

2.2.2. Mineral-associated organic carbon

MAOC, formed through organo-mineral interactions, is stabilized for centuries by adsorption to clay and silt particles [69]. MAOC is a small molecular organic mineral complex with comparatively low carbon/nitrogen ratios (C/N ratios) [70,71]. MAOC has two advantages over POC—first, it has a longer residency duration. Second, it is less vulnerable to rising global temperature (Fig. 3) [51,72].

Global assessments of soil carbon sequestration capacity often overlook the more stable portion of the total soil carbon pool, which is composed of MAOC. MAOC tends to respond positively to the long-term use of cover crops. Cover crops improve soil organic matter by increasing the input of plant residues, which can interact with soil minerals to form stable carbon fractions [73]. Soil mineralogy, environmental variables, and land use practices influence the stability of MAOC. Zhang et al. (2023a) study found that exogenous carbon input significantly increased MAOC content by 89 % and POC content by 85 % in forest soils [74].

3. Soil Inorganic carbon (SIC)

SIC is a crucial component of the total terrestrial carbon stocks. Carbonates (CO₃^{2−}) and bicarbonates (HCO₃[−]) of Ca²⁺, Mg²⁺, K⁺, and Na⁺ make up the majority of SIC [75]. The ratio of precipitation to evapotranspiration is commonly recognized in scholarly works, and identified as the primary factor impacting the allocation of SIC globally [76]. SIC, which accounts for 38 % of global reserves and is surpassed only by SOC, is one of the significant carbon sinks in the apparent ecosphere [77]. Aside from regulating pH, SIC and dissolved Ca²⁺ from carbonates enhance the plant development by increased nutrient availability, root growth and pathogen protection. These processes also

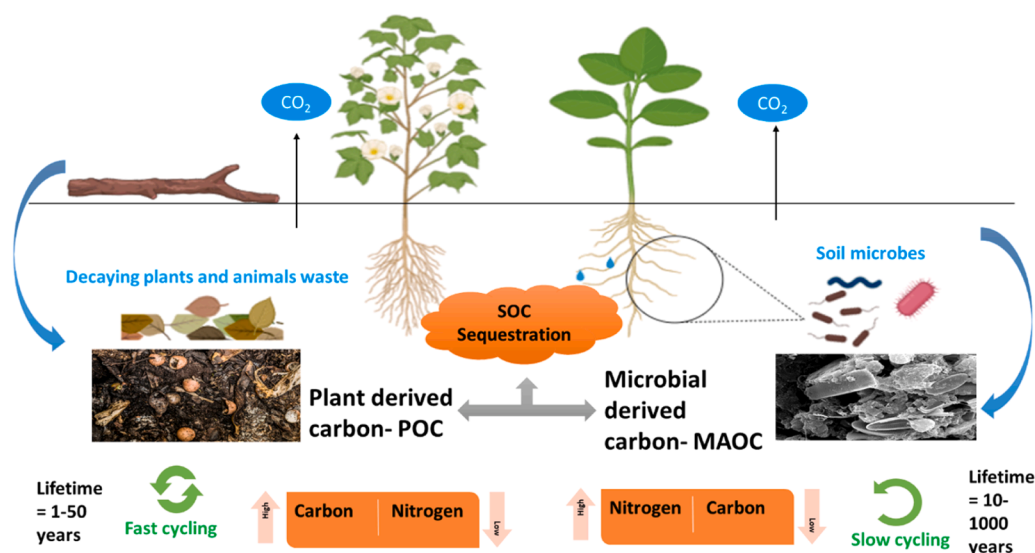


Fig. 3. Formation and functioning of particulate and mineral-associated organic carbon.

help microorganisms mineralize nutrients and promote binding to organic molecules, which stabilize the SOC [10]. The two most significant variables influencing SIC concentration were soil type and pH. Decreased pH in acidic soils may inhibit carbonate production [18]. Fertilization and irrigation had little impact on SIC content, whereas land use modification and agriculture dramatically raised it by 9.25 % and 6.55 %, respectively [78]. According to another study on Chinese croplands, SIC stocks in the 0–40 cm soil layer have dropped by 27–38 % over the last 30 years, while soil pH has dropped by 0.53 units [79]. The main factors contributing to SIC loss are nitrogen fertilization and water balance. While SIC rose in severely dry regions, it fell precipitously in wet and semi-arid areas.

3.1. Geogenic or lithogenic carbonates

Primary/geogenic carbonate is formed from soil or parent rock that has not been weathered or exchanged with the surrounding soil [80]. The three most common inorganic carbonate forms found in soils are aragonite (a polymorph of CaCO₃), dolomite (CaMg (CO₃)₂), and calcite (CaCO₃) [8]. These minerals are crucial for balancing the soil pH which affect soil fertility. According to Zethof et al. (2019), three techniques for detecting and measuring geogenic organic carbon in soils are smart combustion, thermogravimetric analysis (TGA), and Fourier-transform infrared spectroscopy (FTIR) [81].

3.2. Pedogenic carbonates (PC)

PCs are formed from carbonate re-precipitation due to microbial respiration and soil CO₂ dynamics. They are more dynamic and respond to various land use changes [80]. The general procedure to develop a PC consists of three steps:

- SIC pool breakdown - $\text{CaCO}_3 + 2\text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) + \text{H}_2\text{CO}_3(\text{aq})$. In the presence of additional ions like Ca²⁺ and Mg²⁺, bicarbonate hydrolyzes and creates PC as water dissolves the CO₂ from soil respiration and the surrounding environment [82].
- Transport of ions that are dissolved inside pore spaces.
- Re-precipitation via soil profile and surroundings.

Climate, temperature, and precipitation are the most crucial elements influencing PC development and placement. As a result, high temperature promotes PC deposits [83]. A range of 22 kg m⁻² to 108 kg m⁻² of PC in New Mexico is influenced by soil depth and leaching, as

reported by Gile (1995) [84]. With turnover times ranging from hundreds to thousands of years, Landi et al. (2004) found that PC in Saskatchewan accumulated more in higher landscape elevations, with an average of 15 kg C m⁻² in a 1 m soil depth [85]. They also found that PC accumulation rates are 1.4 times higher than organic carbon sequestration. However, SIC does not cycle as actively as SOC, its accumulation and dissolution can significantly influence GHG fluxes and soil chemistry, especially in alkaline environments [86,87].

4. Environmental Drivers of carbon fraction dynamics

A wide range of variables, collectively called “drivers,” influence SOC and SIC levels directly or indirectly. SOC is strongly influenced by the soil’s biological, physical, and chemical properties. Microbial activity, root interaction, and enzyme functions regulate the breakdown and stabilization of organic matter. Physical traits like texture, structure, and porosity affect moisture, aeration, and protection of SOC within aggregates. Chemical factors like as pH, nitrogen levels, and mineral content govern breakdown and carbon retention, therefore determining SOC stability [88].

4.1. Soils pH and texture

Soil pH governs the microbial community structure and enzyme activity. In acidic conditions, SOC decomposition is fast, leading to the accumulation of labile carbon fractions. Meanwhile, SIC dissolution is enhanced, releasing CO₂ and calcium ions [89]. In alkaline soils, carbonate formation is enhanced, contributing to the accumulation of pedogenic SIC [90]. Fine-textured (clay/silt) soils promote MAOC formation by protecting organic matter from microbial decomposition through clay organic complexes and aggregate formation, while sandy soil favour labile fractions due to less physical protection [35]. Hence, clayey soils can store two to four times more RC than sandy soils under similar conditions. Clay-rich soils in the Mun River Basin had higher TOC and TON due to enhanced physical protection of MAOC [91]. Srinivasarao et al. (2014) assessed carbon sequestration in major soil types of semiarid tropical India by estimating SOC and SIC [92]. Red, alluvial, and black soils showed the highest SOC, while SIC was greatest in alluvial and arid soils. In arid soils, most carbon occurs as stable calcium carbonate, making it less available to microbes, while high temperatures accelerate SOC decomposition. Sandy soils have more LOC fractions with faster turnover, while neutral pH supports microbial activity and SOC stabilization. In clayey soils under alkaline conditions, SIC

dominates (Fig. 4).

4.2. Microbial Community and carbon use efficiency (CUE)

Microorganisms are central agents in fraction turnover. Their CUE (the carbon assimilated vs. respired ratio) determines whether SOC is stabilized or lost as CO₂. High CUE supports MAOC formation and SOM buildup [79]. Mycorrhizal fungi aid in transferring plant-derived C into the soil and stabilizing organic matter. Microbial activity can also promote SIC formation by altering soil chemistry (Methane oxidation, ureolysis, ammonification, denitrification, sulfate reduction and anaerobic sulfide oxidation) [93,94]. The two primary methods by which plants sequester carbon in soils are through above-ground plant inputs, such as plant litter and related leachates (such as DOC), and below-ground plant inputs, such as rhizodeposition, root litter, and exudates. These processes extensively depend on soil microbes, which use a range of direct and indirect processes to help cycle and retain soil carbon (Fig. 5) [95,96]. Hu et al. (2025) conducted a global analysis of 670 measurements across forests, grasslands, and croplands, showing that microbial CUE changes with biome and measurement method, with the highest values in grassland soils. They showed that faster microbial growth improves CUE by reducing carbon losses. Growth rates were linked to SOC, nutrients, and the fungi-to-bacteria ratio [97]. These results that soil properties and climate play a important role in controlling microbial activity and long-term carbon storage. Microbial CUE is a central but variable regulator of SOC dynamics, and its integration into Earth system models is essential for improving predictions under global change. Microbial metabolism not only mineralizes labile fractions but also mediates the conversion of organic residues into recalcitrant carbon, affecting both SOC and SIC pools.

4.3. Temperature and moisture

Temperature and precipitation are key climatic drivers of carbon dynamics. Warmer conditions accelerate microbial respiration and enzymatic degradation of labile carbon, particularly DOC and POC [98, 99]. MAOC and humic substances, being chemically bound or mineral-associated, exhibit more resistance to temperature-induced decomposition [57]. Rainfall improves soil moisture content, which stimulates plant growth, increases biomass inputs, and favors microbial processes that contribute to SOC stabilization. It also facilitates leaching of DOC into deeper horizons, reducing decomposition losses. Higher moisture levels promote soil aggregation, which physically protects

organic matter and enhances long-term SOC storage [100]. SIC tends to accumulate in arid and semi-arid environments, whereas SOC builds up in wetter, cooler climates [101]. Study conducted by Wang et al. (2023) examined that how SOC fractions and carbon pools in a wet meadow on the Qinghai-Tibet Plateau were affected by the frequency of heavy rainfall [99]. POC concentration increased and DOC content decreased in the 0–10 cm soil layer as rainfall frequency increased, which substantially impacted SOC fractions. Srinivasarao et al. (2021) examined SOC, SIC, and total carbon stocks under different crop productions across tropical India with rainfall up to 1100 mm. They found SOC to be positively correlated with mean annual rainfall (Table 1) [102]. Han et al. (2017) further reported that precipitation strongly shaped soil microbial communities, with greater sensitivity in surface soils compared to subsurface layers [103]. Past climate conditions need to be included in SOC models to better predict soil responses to changing moisture patterns.

5. Land Use and management impacts on soil carbon fractions

Deforestation and other land-use changes lower SOC, but sustainable practices raise it. Winkler et al. (2021) reported that in the past 60 years (1960–2019), land-use changes have affected nearly thirty percent of the global geographical area [104]. According to the estimate, the top 2 m of soil has a 116 Gt carbon debt due to natural ecosystems being converted to agricultural land [105]. Approximately 25–30 % loss of SOC reserves in the tropics is due to the conversion of primary forest to farmland [106]. Changes in land use from naturally occurring vegetation to agricultural land can quickly cause SIC loss because of higher soil water flows [107]. Restoration of SOC typically occurs more slowly than depletion. Land management is another critical factor that influences soil carbon fraction transformation. Sharma et al. (2022) examined how various land-use practices affect the SOC pool and the biological characteristics of soil in a dry, mountainous region of the Himalayas [108]. This study reveals that mono-cropping and double-cropping systems significantly decrease TOC compared to agroforestry, orchards, and vegetable farming. The findings emphasize that land-use alterations impact the responsiveness of labile carbon fractions and indicators of soil quality, including MBC and soil protein. The research concludes that agro-forestry systems promote soil carbon stabilization and enhance moisture retention, making them more effective for sustainable soil management and carbon sequestration in sensitive ecosystem. In controlled ecosystem, vegetation is the primary carbon accumulator. Therefore, crop cultivation and land management practices impact the

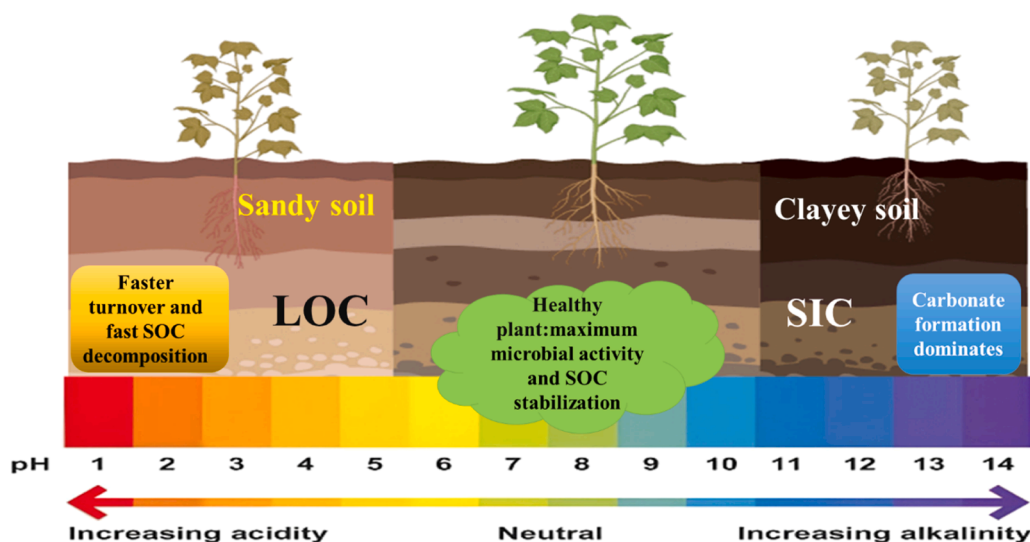


Fig. 4. Effect of soil texture and pH as on soil carbon pools.

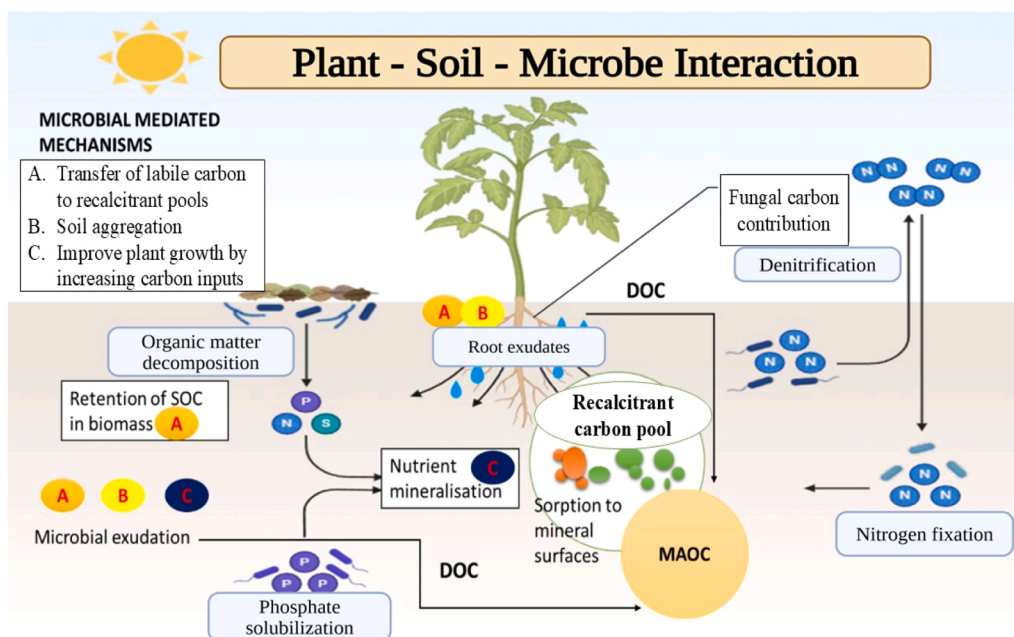


Fig. 5. Contribution of microbes in sequestration and retention of soil carbon. The primary microbially mediated processes that influence soil carbon storage (bubbles A, B, and C) and the microbial activities.

Table 1
SOC analyses of Indian soil about temperature and rainfall patterns.

Mean annual Temperature (°C)	Rainfall (mm/yr)	SOC content (g/kg)	
		Surface	Sub-surface
26–26.7	Less than 500	1.20–8	1.2–4
24–28	500–1000	1.80–12.5	0.7–11.7
24.4–27.2	More than 1000	2.6–9	2.3–8.4

amount of carbon retained in soil. More land-use and land-management initiatives are needed to convert soils into long-term carbon sinks [109]. Meta-analysis by An et al. (2019) comprised 576 data points from 29 studies and shows that converting farmland to grassland causes a 14.4 % drop in SIC, whereas transitioning grassland to farmland causes a notable 30.6 % gain in SIC [110]. The impact of afforestation is different. SIC rises when sand land is turned into forest, but falls when agriculture or grassland is turned into forest. It is crucial to consider certain land-use types and environmental conditions in soil carbon research because of the complex and varied effects of land-use changes on soil carbon fractions. These fractions affect nutrient availability, soil structure, and overall ecosystem health. Soil quality is directly related to their dynamics.

5.1. Biochar

Biochar, a carbon-rich product from pyrolyzed biomass, is considered effective for long-term carbon sequestration [111]. The long-term potential for soil carbon storage attributed to biochar highly relies on its substantial carbon content, heat resistance, and recalcitrance. Since biochar is produced from biomass, its production is a more environmentally friendly and sustainable process that lowers organic waste (from municipalities or agriculture) [112]. Biochar interacts with multiple carbon pools:

- Stabilizes labile fractions by sorbing DOC and POC onto its porous surface.
- Enhances MAOC formation through mineral association.
- Alters soil microbial community structure, boosting CUE [93,94]

- Biochar also increases soil pH, improving SIC formation in acidic soils [113].
- It can reduce CO₂ and N₂O emissions by modifying microbial pathways [114].

Biochar application to loamy soil led to stable SOC sequestration over an eleven-year study in Germany [115]. The effects of biochar on SOC dynamics in a paddy field over four years are examined by Song et al. (2024) [116]. Biochar, particularly when combined with maize straw, lowered net carbon mineralization and SOC mineralization by 13.5–27.8 % in a 60-day incubation experiment using soils from depths of 0–15 cm, 15–30 cm, and 30–50 cm. Fungal and gram-positive bacterial activity in subsoil was enhanced by biochar, which also raised MBC and enzyme activity in topsoil. Numerous mechanisms, including enhanced carbon sorption, decreased mineralization rates, improved soil aggregation, and changed microbial activity, are involved in how biochar affects soil carbon fractions [117]. Dong et al. (2019) investigated the long-term effects of biochar on SIC in a calcareous soil profile in China [118]. The rates at which biochar was applied were 0, 30, 60, and 90 t ha⁻¹. Biochar at 30, 60, and 90 t ha⁻¹ raised SIC by 7.8 %, 20.2 %, and 28.3 %, respectively. The porous nature of biochar enhances microbial activity and soil aeration. By breaking down organic materials, microorganisms release CO₂, which combines with calcium to form carbonates and raises the SIC. Table 2 shows various biochar feedstocks and their effect on GHG emissions and crop yield.

5.2. Tillage and cropping system

Conventional tillage disturbs soil aggregates, exposing protected organic matter and increasing the mineralization of labile fractions like POC and DOC [137]. This results in short-term CO₂ release and reduced microbial biomass, undermining long-term carbon stabilization. Conservation tillage and no-till practices preserve soil structure, enhance MAOC accumulation, and retain microbial activity. Studies show reduced disturbance supports recalcitrant carbon pools and slows SOC turnover [55]. Crop diversification and perennial systems further support labile fractions by increasing below-ground biomass and microbial exudates, fostering DOC and LFOC development. A study conducted by

Table 2
Effect of biochar on GHG emissions and crop yield.

Feedstock for biochar	Application rate	Pyrolysis temperature (°C)	pH	EC (µS/cm)	CEC (cmol/kg)	Bulk density (g/cm ³)	C (%)	H (%)	N (%)	S (%)	K (mg/kg)	P (mg/kg)	Mg (mg/kg)	Parameter	Impact	Reference
Rice straw	250 kg/ha	500	9.04	-	27	0.27	50.55	1.79	1.89	0.17	8900	-	-	CH ₄ and N ₂ O emissions	Reduced by 27.80 % and 30.56 % respectively	[119]
Mangrove (rhizophora apiculata) biochar	10 t/ha	600	-	-	-	-	58.5	-	0.28	-	1800	2300	11,200	CH ₄ emission	Decreased by 25 %	[120]
Rice straw	8 Mg/ha	600	6.5	1200	-	1.1	81.35	2.42	0.12	-	-	1100	-	CH ₄ emission	Reduced by 7.37 %	[121]
Rice straw	20 Mg/ha	400–500	10.58	-	50.6	0.35	47.21	1.4	1.08	-	-	-	-	N ₂ O emission	Reduced by 65.46 %	[122]
Switchgrass	10 Mg/ha	700	10.8	550	19.2	-	49.5	-	0.45	-	-	-	-	CO ₂ emission	Reduced by 17.94 %	[123]
Pine wood	10 Mg/ha	600	9.3	120	9	-	55	-	0.33	-	-	-	-	CO ₂ emission	Reduced by 13.04 %	
Corn stover	10 Mg/ha	500	10	800	24.1	-	48	-	0.41	-	-	-	-	CO ₂ emission	Reduced by 19.90 %	
Corn straw	64 Mg/ha	550	10.46	-	-	-	75.3	-	1.23	-	-	-	-	CO ₂ and N ₂ O emissions	Reduced by 59.98 % and 18.33 %	[124]
Blue mallee Wood	10 Mg/ha	500	9.6	340	-	-	54.9	-	1.4	0.055	6500	2400	900	CO ₂ emission	Reduced by 18.24	[125]
Hardwood	-	500	6.8	700	-	-	66.2	-	3.2	-	34,000	3000	-	N ₂ O emission	Decreased by 50 %	[126]
Wheat straw	20 Mg/ha	450	9.93	-	39	-	69	2.8	0.3	0.2	26,000	-	133	Barley yield	Increased by 20.37 %	[127]
Corn straw	30 Mg/ha	500	9	-	-	-	47.2	3.8	0.7	-	783.9	394.2	-	Corn yield	Increased by 7.57 %	[128]
Rice husk	22.5 t/ha	500	9.18	347	17.57	0.84	47.8	2.43	-	-	-	-	-	Organic matter	Organic matter increases from 0.91 % to 2.03 %	[129]
Chicken manure	6.43 t/ha	535	6.81	-	7	1.52	32.8	-	3.5	0.005	505	342	147	CEC	Increased from 6.28 to 7.01	[130]
Wheat straw	5 % and 10 %	350–550	9.9	1000	21.7	0.40	60.5	3.5	0.59	0.5	11,500	14,430	-	Okra crop	Improved plant growth	[131]
Sewage sludge	5,10,15,20 % (w/w)	600	6.87	-	-	0.97	24.33	-	0.17	-	270	1710	-	Ryegrass and cucumber	Promoted plant growth by 54 %	[132]
Corn straw	4500 kg/ha	400	8.92	110	35.6	0.32	58.2	3.21	1.12	0.18	14,200	1320	1180	Organic matter	Increased by 7.2 %	[133]
Maize Straw	1 % and 4 % (w/w)	400	7.08	-	14.53	-	62.74	-	2.27	-	-	-	-	SOC and GHGs emissions	SOC increasing by 68.3 % CO ₂ and N ₂ O emission decreased by 24.1 % and 64 %	[134]
Pine Residue	0.5,10,20 t/ha	380–550	5.84	-	-	-	55.97	-	0.59	-	2100	90	90	SOC	Moderately increasing	[135]
Maize Stalk	0.5,10,20 t/ha	380–550	9.31	-	-	-	45.67	-	0.65	-	19,800	3570	160	French bean yield	High yield improvement	
Cymbopogon Winterianus waste	2,4,6,8 % (w/w)	450	8.2	168	125.3	0.97	58.39	3.94	1.2	-	-	2530	-	Soil and plant properties	Improved soil fertility and enhanced plant growth	[136]
		850	9.3	193	87	0.85	67.74	1.89	1	-	-	2250	-			

Holman et al. (2025) on forage crop rotation found that no-tillage improved soil microaggregation, while reduced tillage promoted larger macroaggregates and better weed control [138]. The exposure of stored subsurface carbon to oxidation, dissolution, and leaching causes runoff and carbon breakdown losses, disturbing organic and inorganic carbon stocks. Over time, zero tillage enhanced soil stability and aggregation in comparison to conventional tillage (Fig. 6) [23].

5.3. Organic Amendments and cover cropping

Application of compost, farmyard manure, and green manures boosts both labile (MBC, DOC) and recalcitrant (MAOC) pools. These inputs stimulate microbial metabolism and aggregate formation, enhancing soil fertility and resilience [32,47]. A global meta-analysis showed that nitrogen with manure caused the largest increase in DOC and DOC/SOC ratio, followed by manure, straw, and nitrogen fertilizer. In contrast, biochar improved carbon stability but lowered the DOC/SOC ratio. Organic amendments are useful for lowering CO₂ emissions, improving yields, and strengthening sustainable soil management [139]. Tian et al. (2025) showed that biosolid-amended soils had higher microbial carbon storage, improved biologically active carbon, and greater water-holding capacity, reducing stress and increasing carbon retention [140]. Even after 40 years, these soils maintained much higher SOC (3.18 %) than conventionally fertilized soils (1.26 %), equivalent to a net sequestration of 37.1 Mg ha⁻¹, along with measurable greenhouse gas mitigation. They also provide a net GHG credit of 0.59 Mg CO₂-eq per mg applied. The study demonstrates the potential of biosolids as a sustainable amendment to soil health, support climate-smart agriculture and help achieve global initiatives like 4 miles per 1000 and net-zero targets.

Cover crops enrich soil organic inputs and improve microbial diversity, which helps retain DOC and enhances MBC turnover. They also increase root exudation, an essential carbon source for MAOC formation [34]. POC responds quickly to cover crop incorporation due to its labile nature; MAOC changes are more pronounced over extended periods [71]. Long-term cover cropping increased MAOC in rice-based systems under tropical climate regimes [7]. Cover crops increase the carbon content of the soil by adding organic matter through their root and shoot biomass and by absorbing atmospheric CO₂ during photosynthesis. They also enhance soil structure by promoting soil aggregation and reducing erosion, which helps prevent the oxidation of soil organic carbon [141, 142]. (Fig. 7).

5.4. Agroforestry and integrated system

Agroforestry system provides perennial litter and continuous root inputs further increasing DOC and LFOC. Shaded microclimates reduce microbial respiration rates, slowing carbon loss [143]. Long-term studies showed that such systems significantly enhance both SOC and SIC storage, particularly in degraded lands [144]. Sirimalle et al. (2025) conducted a 37-year study in semi-arid western India comparing *Acacia tortilis*, *Hardwickia binata*, and *Tecomella undulata* agroforestry systems [145]. Results showed that *Acacia tortilis* had the greatest impact on soil carbon storage, with a 42.5 % increase in topsoil TOC, a 68.3 % rise in active carbon pools and 39.34 Mg C ha⁻¹ sequestered across 0–90 cm. Study conducted by Barman et al. (2025) for 15-year in Indian Himalayas found that mulberry with cowpea–toria agroforestry maximized soil carbon, with SOC stocks of 21.35 and 33.52 Mg C ha⁻¹ (surface and deep soil), high labile carbon (6.20 g kg⁻¹), recalcitrant carbon (4.49 g kg⁻¹), and a carbon accumulation rate of 0.99 Mg C ha⁻¹ yr⁻¹, showing its sequestration and restoration potential [146]. Strategies that enhance labile productivity and recalcitrant storage offer the most significant potential for climate-resilient carbon management. Numerous research studies showing various factors and mechanisms influencing soil carbon fractions (Table 3).

6. Soil carbon fractions as indicators of soil health and resilience

Soil carbon fractions serve as reservoirs of organic matter and as dynamic indicators of soil health, ecological balance, and ecosystem resilience under climate and land-use changes. These indicators represent the balance between carbon input and turnover while detecting changes in soil activity, nutrient cycling and degradation.

MBC is one of the most immediate indicators of soil biological status. It comprises less than 4 % of the soil organic matter yet governs crucial processes like carbon mineralization and SOC formation. Research by Sunish et al. (2023) and Das et al. (2023) emphasizes that fluctuations in MBC can provide early evidence of environmental change, management interventions, or microbial stress responses [34,172]. MBC is affected by season, land use, and depth, and is especially responsive to organic amendments and tillage practices. DOC is another critical indicator due to its mobility and role as a microbial substrate. DOC concentrations respond rapidly to precipitation, vegetation type, and microbial activity, reflecting near-term soil biological dynamics [40]. Since it has a short turnover rate and can transport carbon to subsoil layers, it also signals

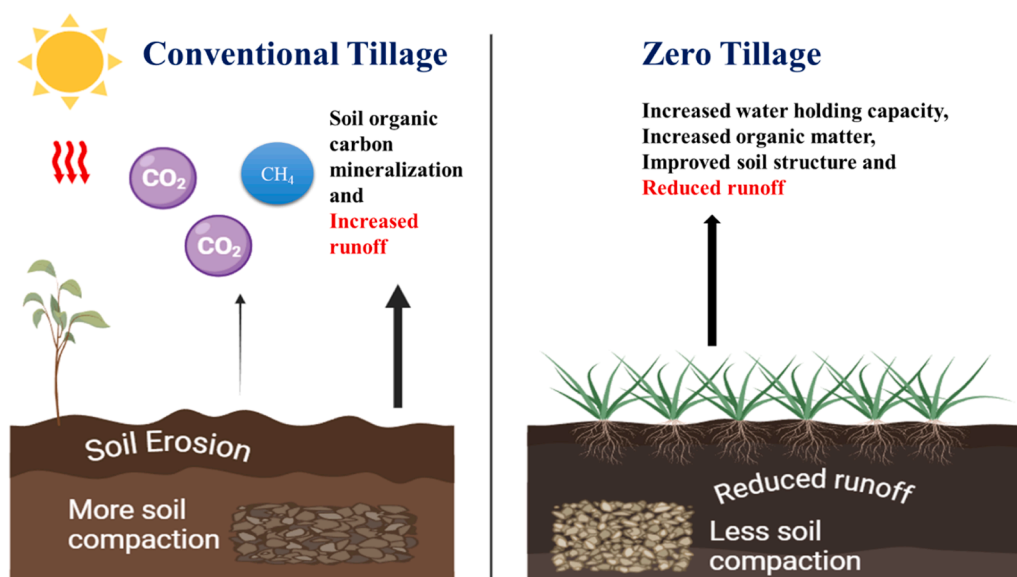


Fig. 6. Advantages of using zero tillage in agriculture over traditional tillage.

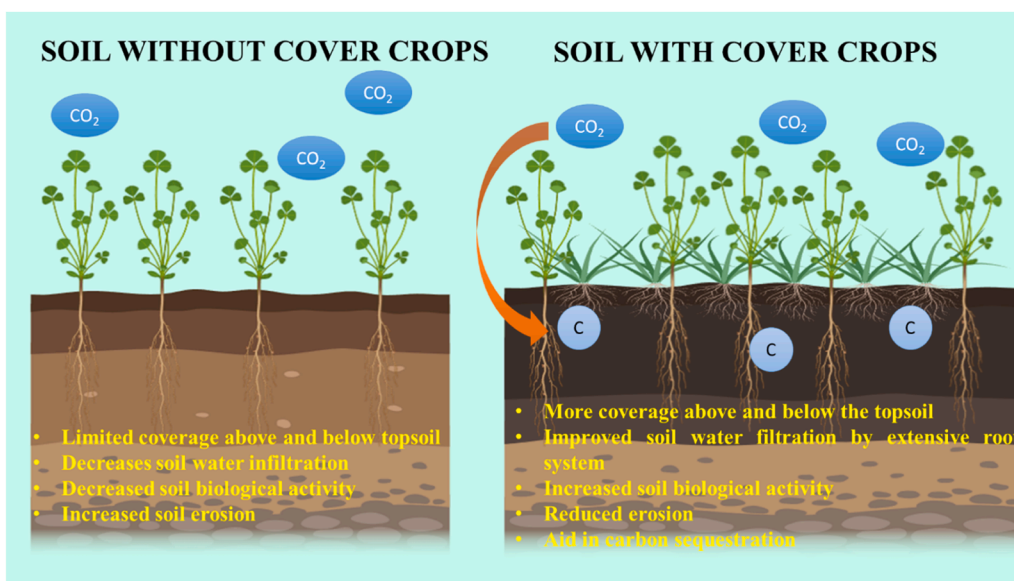


Fig. 7. Comparison of soil functions and carbon sequestration potential with and without cover crop application.

vertical carbon mobility and leaching potential. POC is sensitive to tillage, erosion, and input quality. As a labile but intermediate-term storage pool, it provides insights into organic matter inputs, aggregate stability, and early-stage humification. POC accounts for 20–45 % of SOC in agricultural soils, making it an essential measure for management-induced changes in carbon availability [7,51]—microbial biomass levels, vegetation cover, and surface management influence LFOC. As a short-term indicator of fresh organic matter input and decomposition status, LFOC can reflect the rate of soil recovery in degraded systems [32]. In contrast to these short-lived indicators, MAOC is considered a robust signal of long-term carbon stabilization. It exhibits high resistance to decomposition. Its content increases with soil aggregation, fine texture, and persistent organic input, and it is less affected by short-term environmental variation. According to Zhang et al. (2023a) and Witzgall et al. (2021), MAOC is a reliable marker of sustainable carbon sequestration and soil structural integrity [69,73]. SIC, which is monitored less frequently, also proved to be a valuable indicator, especially in drylands. It helps regulate pH, nutrient availability, and long-term abiotic carbon storage. Its formation and dissolution are affected by water balance, microbial respiration, and soil pH. As noted by Hong and Chen (2022); Zamanian and Kuzyakov (2022), SIC can buffer soil acidity and contribute to soil resilience, particularly in alkaline systems or where pedogenic carbonates are actively forming [13,87].

These carbon fractions act as useful indicators for assessing soil quality and monitoring sustainability. The different turnover rates and sensitivities of these fractions help explain how soils respond to stress and management. They are therefore valuable for guiding restoration and climate adaptation efforts.

7. Modeling carbon fractions in climate-change scenarios

Modeling the dynamics of soil carbon fractions is critical to accurately forecast carbon sequestration under different climatic and land-use scenarios. Earlier models like RothC and Denitrification–Decomposition (DNDC) have traditionally represented soil carbon as broad pools without explicitly accounting for the functional behaviour of labile and recalcitrant fractions. However, as the demand for precise climate-smart agriculture tools grows, it has become clear that models need to move beyond total SOC and integrate the turnover behaviour of microbial, particulate, and mineral-associated carbon fractions. Recent developments have seen the rise of biologically

enriched models that offer greater realism. For instance, the MiPrime model used by Kok et al. (2025) simulated soil carbon pools in agricultural systems and successfully captured microbial biomass, mineralization rates, and both dissolvable and insoluble carbon pool behaviour [173]. The model revealed that while some soluble fractions exhibited positive priming, hot-water extractable fractions showed negative priming, emphasizing the heterogeneity of soil responses to organic inputs. Similarly, Davoudabadi et al. (2023) integrated microbial dynamics into RothC3BIO-K and RothC5BIO-K, significantly improving the predictions by simulating biologically mediated decay [174]. When tested on UK and Australian datasets, these updated models demonstrated high accuracy, suggesting that microbial biomass plays a key regulatory role in the decomposition and stabilization of soil organic matter. Regarding practical applications, DayCent has proven to be one of the most accurate Tier 3 models for assessing SOC variability, as shown in long-term studies using compost-amended soils in the USA. Ball et al. (2023) evaluated several greenhouse gas accounting tools and reported that DayCent explained around 50 % of SOC variability, outperforming COMET-Farm and WaCSE [175]. This accuracy highlights the model's ability to track SOC responses to management practices like organic amendments and conservation tillage. Advancements have also been made in spatial SOC prediction. Ji et al. (2024) employed hybrid modeling using Sentinel-2 imagery and kriging-based techniques to develop highly accurate SOC maps for Germany [176]. The study found that SOC varied significantly across land-use types, emphasizing the need for spatially aware SOC monitoring at national scales.

Despite these developments, challenges persist. A significant limitation remains the scarcity of long-term, high-resolution data on carbon fractions, especially under diverse agroecological conditions. Furthermore, while SOC is increasingly modeled with biological resolution, SIC remains underrepresented. The current models often omit SIC transformations and the interplay between carbonates and microbial activity, which is particularly relevant in arid and semi-arid zones. Modern models are increasingly capturing the complexity of SOC dynamics. Future models should also include SIC behavior, carbon priming effects, microbial interactions, and the influence of land use. Simulating carbon at the fraction level has moved from being a theoretical idea to a practical tool, important for guiding carbon farming, certification programs, and global soil restoration efforts.

Table 3
Effects of environmental and management factors on soil carbon fractions with evidence from global studies.

Factor	Mechanism	Effect on Soil carbon fractions	Location	References
Temperature and precipitation	Rising temperature reduces microbial residue carbon (MRC) and weakening SOC accumulation	SOC declined with increasing mean annual temperature, fungal MRC exhibited greater stability than bacterial MRC	Tibetan Plateau and Shennongjia Mountains, China	[147]
	Colder and humid temperate conditions reduce decomposition, SOC fractions consistently higher in temperate than subtropical soils.	Temperate soils hold 30.7 % more TOC than subtropical soils	North Western Himalaya, India	[148]
	Moderate soil moisture enhances aerobic activity, aggregation, and C stabilization Soil moisture gradient (10–90 % WHC), Moisture regulates microbial respiration from LOC and native SOM	SOC increased in macroaggregates, enzyme activity maximized at 65 % saturation CO ₂ flux maximized at 60 % WHC, LOC-derived respiration increased below 60 % WHC; SOM decomposition increased above 60 % WHC	Wuxue, Hubei Province, China Semi-arid temperate forest, China	[149] [150]
Soil pH and Texture	Clay content and soil pH strongly regulate SOC and TN retention; land use alters vertical distribution	Higher SOC in forest and paddy soils with clay texture; lower SOC in sandy soils and degraded lands	Mun River Basin, Northeast Thailand	[90]
	Acidification reduces microbial decomposition and promoted mineral protection of plant-derived C	POC increased by 19–22 % (0–20 cm); MAOC increased by 8–23 % (10–20 cm); microbial residue C decreased	Dinghushan Biosphere Reserve, South China	[151]
	Low sand content provides greater mineral surface area for MAOC stabilization Texture regulates porosity, moisture retention, and organic input stabilization	MAOC formation efficiency higher in fine-textured soils SOC storage: Sandy loam (68.4 t ha ⁻¹) > Silt loam (63.7) > Loam (38.1) > Clay loam (31.3); (0–30 cm depth)	10 agricultural sites across Canada Ethiopia, Africa	[152] [153]
Organic amendments	Manure affect SOC physical and chemical fractions	SOC, MBC and POC increases by 2.03 %, 9.26 %, 3.74 % resp.	Foothill Himalaya, India	[154]
	Organic inputs affect SOC stabilization Shifts in microbial community structure	POC and MAOC increase by 410.9 % and 43.5 % resp. TOC, LFOC and MBC increased by 5.6–10 %, 64–89 %, 83–106 % resp.	Zhejiang Province, China Heilongjiang, China	[155] [156]
	Rebuilds soil structure; POC from Structural Plant Carbon and MAOC from Hot Water Extractable Carbon	SOC increased by 48 % in high-aggregation soils and MAOC by 20 %	Kansas and Colorado, USA	[157]
Zero-Tillage	Enhances macro-aggregates and pore connectivity, stabilizing SOC	51–54 % increase in macro-aggregates	New Mexico, USA	[158]
	Improves aggregate stability; enhances labile and recalcitrant fractions	TOC increases from 1.4 % to 2.2 % in macroaggregates (0–10 cm)	Botucatu, São Paulo, Brazil	[159]
	Promotes residue retention and legume integration	72.3 % increase in TOC (0–5 cm); 93.8 % increase in POC	Karnal and Samastipur, India	[160]
Microbial Activity	Improves SOC stratification, reduces disturbance and enhances surface carbon storage	SOC increased by 95 % (15 cm)	Southern Blue Ridge, USA	[161]
	Enhanced fungal biomass and microbial necromass; improves DOC availability	SOC increased by 39–40 % and aggregate stability doubled	Hollabrunn, Austria	[162]
	Soil microbial community regulates SOM decomposition, aggregate formation, and necromass stabilization	Microbial necromass contributes >50 % of SOC in croplands, macroaggregate stability increases by approx. 85 %	Meta analysis (197 studies)	[163]
Cover cropping	C mineralisation rose due to activation of C-degrading enzymes	SOC decreased; bacterial diversity declined, fungal diversity increased	Forest plantations, China	[164]
	Improves SOC sequestration, nutrient cycling, microbial biomass; reduces fertilizer demand and erosion	SOC sequestration (1.43 Mg CO ₂ eq ha ⁻¹ yr ⁻¹); Net climate mitigation (3.30 Mg CO ₂ eq ha ⁻¹ yr ⁻¹)	European Union countries	[165]
	Enhances SOC sequestration, microbial activity, and nutrient cycling	Sunn hemp and crimson clover increase SOC by 38 % and 3 % resp.	Southern Coastal Plain, USA	[161]
Land use/ Agroforestry	Legumes fix N biologically, boosting yield and SOC	Average increase in SOC by 5.9 % (legume) and 4.0 % (non-legume); yield increases by 16 % (legume)	Global meta-analysis (271 studies)	[166]
	Conversion of forest to agriculture, horticulture, and plantations; changes SOC pools	SOC decreased by 82 % in agriculture soils (Active pool-15.17 g/kg) vs. evergreen forest had highest active pool (52.71 g/kg)	Kolli Hills, Eastern Ghats, India	[167]
	Long-term forage cropping enhance SOC	Increased SOC stock (52.74 Mg ha ⁻¹), TOC (7.20 g/kg), and LOC (104.8 %) compared to uncultivated soil	Ghaggar Flood Plains, Rajasthan, India	[168]
	Vegetation restoration enhances litter and root inputs; improves biochemical stability	SOC increases by 123 % in climax forest compared to abandoned cropland (0–20 cm)	Ziwuling Forest, Loess Plateau, China	[169]
	Woody perennials enhance microbial biomass, increase litter and root-derived inputs, and concentrate SOC in surface layers	SOC increased by 15 %, MBC increased by 25 % and sequestration rate is 0.4 Mg C ha ⁻¹ yr ⁻¹	Iowa, USA	[170]
	Forest to grassland conversion reduces litter input and microbial biomass; higher bulk density and CO ₂ release	SOC, SOC stock, MBC decreased by 36.1 %, 1.5 % and 29.5 % resp.; CO ₂ -eq increased to 23 Mg ha ⁻¹	India (31 sites)	[171]

8. Strategies for enhancing soil carbon sequestration

Enhancing the sequestration of soil carbon fractions requires a in-depth understanding of how various agricultural interventions influence the dynamics of labile and recalcitrant pools. With growing emphasis on sustainable agriculture and climate-resilient practices, fraction-level strategies offer a promising path to increase long-term SOC storage and ecosystem stability.

Cover cropping is one of the most widely recommended techniques, and it has demonstrated significant potential to improve MBC and

MAOC. Acharya et al. (2024) evaluated that in semi-arid irrigated cropping systems, cover crops increase SOC storage by 10–17 % and improve soil health indicators like MBC by 19 %, MAOC by 11.75 %, and POC by 42.75 % [177]. The fungus-to-bacterial ratio is larger when compared to no cover crops, suggesting that cover crops also enhance the bacterial and fungal communities. Additionally, cover cropping promotes the formation of soil aggregates, stabilizes POC, and enhances soil structure and water retention capacity. Chahal et al. (2020) observed that cover crops increased SOC by 10–20 Mg C ha⁻¹. The study also found that cover crops improved crop yield and reduced yield

variability, enhancing agroecosystem resiliency [178]. Zero tillage and conservation tillage are also essential practices that protect SOC by minimizing soil disturbance. These methods enhance macroaggregate formation and reduce the decomposition of organic matter. Over time, no-till systems show improved soil aggregation, stability, and carbon stocks in upper soil layers (0–20 cm). Cooper et al. (2021) reported that zero tillage significantly improved pore connectivity, reduced macroaggregate porosity, and protected SOC in Brazilian tropical soils [159].

Biochar amendment represents a promising approach in long-term carbon stabilization. Its effect on carbon fractions is multifaceted: biochar enhances POC, stabilizes DOC through sorption, promotes microbial activity, and even contributes to the formation of pedogenic inorganic carbon by facilitating carbonate precipitation. Zhang et al. (2024a) found that biochar increased SOC sequestration by 46 % and maize yields by 14 % in saline-alkaline soils while reducing CH₄ and N₂O emissions by 6 % and 16 %, respectively [179]. Its porous nature also enhances microbial habitats, supporting biological processes that favour stable SOC formation. Biochar's influence varies by feedstock and pyrolysis conditions. According to a meta-analysis by Meng et al. (2024), manure-based biochar increased SOC by up to 50.5 %, with notable gains in MBC and DOC but differing impacts on CO₂ emissions depending on the material used [180]. This makes biochar a context-specific tool, especially effective when integrated with organic fertilisers or irrigation adjustments. Manuring and residue management further complement these strategies by enriching labile carbon fractions and supporting microbial-driven humification processes.

Conservation agriculture, which includes mulching, residue retention, and crop rotation, is particularly effective in soils with low initial SOC levels. These practices stimulate the buildup of microbial and humic pools, gradually transitioning labile inputs into more stable forms like MAOC and HS. Lastly, agroforestry and land-use diversification play a transformative role. Systems integrating perennials provide year-round litter and deep-rooting biomass, increasing DOC and MAOC while moderating microclimatic variability. Thangavel et al. (2018) showed that conversion from abandoned farmland to fruit orchards enhanced SOC fractions and improved soil respiration dynamics, even in degraded ecosystems [181]. Optimizing carbon sequestration requires a portfolio of practices targeted at specific carbon fractions. Combining conservation tillage, biochar, organic amendments, and biodiversity-enhancing strategies like agroforestry offers a holistic path toward soil restoration, climate mitigation, and sustainable food systems (Fig. 8) [182].

9. Conclusion and future directions

Soil carbon fractions are central to understanding and harnessing the full potential of soils in climate mitigation, food security, and sustainable land management. Each fraction whether labile like MBC, DOC, and POC, or stable like MAOC and SIC, plays a distinct yet interconnected role in driving soil function, resilience, and long-term carbon sequestration. This review highlighted the complex relationship between soil carbon and environmental factors such as land-use systems, and agricultural interventions. Effective soil carbon management must go beyond increasing TOC; it must consider the stability, turnover, and transformation of individual carbon pools. Land-use management strategies such as reduced tillage, cover cropping, and biochar application have been proven to enhance advantageous microbial populations and eventually increase the storage of SOC. Biochar has emerged as a promising strategy for long-term carbon retention and emission reduction due to its physicochemical stability and influence on microbial pathways. Similarly, cover cropping improves microbial activity and aggregate formation, which enhances the buildup of stable pools.

A holistic understanding of the soil carbon pools and their interactions with biotic and abiotic factors helps arrive at more efficient strategies for managing soil health. Accurately predicting soil carbon dynamics in different settings remains a major challenge. Further work on modeling accounting for abiotic factors such as temperature, moisture, texture and biochar that have significant effects on the soil carbon fractions can help reduce the methodological variability and arrive at congruence. The saturation level of SOC remains a theoretical boundary that requires region-specific quantification and experimentation. Understanding how much more SOC can be sequestered at the fraction level and under which management regimes is critical. The "4 per 1000" initiative provides a useful benchmark, proposing that a 0.4 % annual increase in SOC can significantly offset anthropogenic GHG emissions. However, its success requires technical solutions and proper modeling, especially in India, where SOC stocks are low and resource constraints are high.

At the same time, comparing SOC and SIC remains challenging. Their origins, turnover rates, depth distributions, and sensitivities to environment factors differ significantly. SOC largely affected by microbes and land-use factors, while SIC by geochemical and pH-related processes. Current models often fail to capture both pools simultaneously, creating gaps in carbon accounting. Integrated frameworks are essential to align SOC and SIC research, enabling more accurate predictions of soil carbon dynamics under climate change. Future work should focus on advancing fraction-specific modeling, developing tools for real-time monitoring, and incorporating both pools into assessments. Research

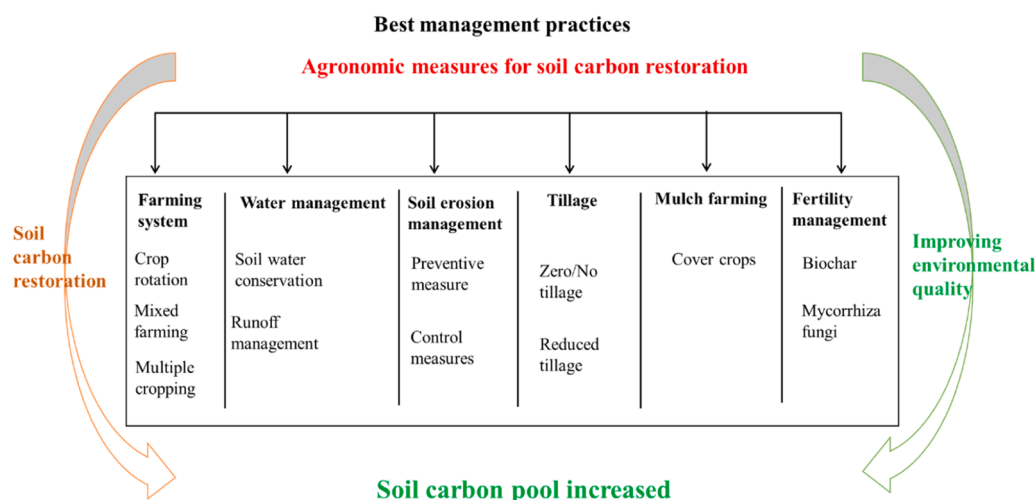


Fig. 8. BMPs to increase the soil carbon pool.

should also focus on advancing carbon farming in development programs.

Soil carbon management aligns directly with global sustainability targets. Restoring soil carbon fractions is not only important for the environment but also provides socio-economic benefits and helps build a more resilient future. Managing carbon fractions offers a practical and scientific way to address climate change by reducing GHG emission and contribute to achieving SDG 13. Using strategies that consider soil carbon fractions in land use and carbon farming can greatly increase carbon storage, restore soils, and strengthen ecosystems. Carbon rich soil are not only more productive but also act as a safety measure for farmers, helping them cope with uncertain rainfall and degraded land. This approach also supports sustainable development by improving food security (SDG 2) and promoting ecosystem conservation and land sustainability (SDG 15). SOC is a key indicator of SDG 15.3 (Land Degradation Neutrality), where building SOC stocks is recognized as a measurable pathway to halt and reverse land degradation.

CRediT authorship contribution statement

Meenu Yadav: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Rishi Mittal:** Writing – review & editing, Conceptualization. **Anu Kumari:** Writing – review & editing, Visualization. **Archna Bhatia:** Writing – review & editing, Visualization. **Amita Khatri:** Visualization, Conceptualization. **Rachna Bhatia:** Validation, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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