

Review Article

Mechanisms and Processes of Soil Organic Carbon Sequestration in Ethiopia: A Review

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Abstract

Photosynthesis, litter decomposition, and root exudation are key processes contributing to organic carbon sequestration in ecosystems. Soil organic carbon (SOC) is a heterogeneous mixture of organic components, including microbial biomass, plant and animal residues, simple sugars, complex organic compounds, and carbohydrates. Globally, soils contain an estimated 1,550 Pg of organic carbon. However, historical land conversion for agriculture has caused substantial carbon losses, with approximately 78 Pg lost mainly through erosion and mineralization. In Ethiopia, SOC loss is similarly attributed to soil erosion and land use change, with estimates ranging from 15 to 1,000 kg ha⁻¹ yr⁻¹. SOC sequestration occurs through various mechanisms, including carbon inputs from plant litter, crop residues, and rhizodeposition. The stabilization of SOC plays a vital role in the long-term storage and protection of carbon in soils. Physical protection involves strong chemical bonding between SOC and the soil's mineral matrix and the physical inaccessibility of SOC to decomposers. Biological protection involves the encapsulation of SOC within soil aggregates and hydrophobic domains of soil organic matter. Overall, SOC storage is influenced by complex interactions among soil, plant systems, and management practices. Effective soil management strategies can significantly enhance SOC sequestration in croplands.

Keywords

SOC Dynamics, Carbon Storage, SOM

1. Introduction

Enhancing or maintaining SOC stocks is categorically a win-win strategy that yields numerous benefits at various scales, such as mitigating climate change, halting soil degradation, guaranteeing agricultural sustainability, improving biodiversity, and raising farm productivity and profits. Organic carbon sequestration, the process by which carbon dioxide (CO₂) is captured from the atmosphere and stored in organic matter, holds great promise as a viable solution. Organic carbon sequestration plays a crucial role in mitigating climate

change by reducing the concentration of CO₂ in the atmosphere [1]. By storing carbon in organic matter, such as plants and soils, it helps to offset anthropogenic carbon emissions and slow down the rate of global warming. Additionally, organic carbon sequestration has numerous co-benefits, including improving soil fertility, enhancing water retention capacity, and supporting biodiversity conservation. Understanding the mechanisms and processes underlying organic carbon sequestration is crucial for developing informed strategies to enhance

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carbon storage and combat climate change. Photosynthesis serves as a cornerstone mechanism in the carbon sequestration process. Through photosynthesis, plants utilize sunlight, carbon dioxide, and water to produce organic compounds, capturing atmospheric CO₂ and converting it into organic carbon. This stored carbon becomes part of the plant biomass, contributing to the overall carbon pool.

According to [2] there was a direct correlation between the breakdown of litter and the build-up of soil organic carbon throughout all ranges that illustrate this relationship. The carbon variation among different components would be based on various factors such as age of the vegetation, density, anthropogenic activities and seasonal variation has great impact on litter carbon [3]. In addition to photosynthesis and litter fall, root exudation contribute to organic carbon sequestration because of Root exudates are rich in organic compounds [3]. Root exudates can function as a source of soil organic carbon (SOC) that can be stabilized through various mechanisms leading to long term sequestration. Plant roots exudates consists of 10-40% carbon, primary and secondary metabolites, mucilage, protein, srringolactones, phytohormone, steroids, terpenoids, fatty acids, and nucleotide derivatives. Plant roots exudates analysis recent advances and application research-ge, and their subsequent decomposition by soil microorganisms enhances carbon storage in the soil, promoting the formation of stable organic carbon [3].

Beyond the natural processes involved in organic carbon sequestration, various management practices and land-use strategies can significantly impact carbon storage potential. As reported that [4] SOC can be preserved by using crop rotations with reduced tillage frequency and additions of chemical fertilizers, crop residues and/or. Similarly, using a combination of both mineral fertiliser and organic fertiliser seems most promising for increasing crop yields, increasing nutrient use efficiency and sequestering soil carbon. For instance, practices such as agroforestry, cover cropping, and improved land management techniques can enhance carbon sequestration in agricultural systems. Similarly, restoration of degraded ecosystems, and reforestation efforts have the potential to sequester substantial amounts of carbon in forests and other natural landscapes [5]. While organic carbon sequestration offers significant benefits in terms of climate change mitigation and ecological sustainability, it is not without challenges. Factors such as land-use changes, climate variability, and potential carbon loss from disturbed ecosystems can hamper the effectiveness of carbon sequestration efforts [6]. Additionally, the long-term monitoring and assessment of carbon sequestration projects are critical to ensure their success and inform future strategies [7]. The potential gap that motivated us to write this review on soil organic carbon sequestration in Ethiopia is, topic that has not been adequately understood, and explored. This review presents a comprehensive examination of the mechanisms and processes involved in organic carbon sequestration. By examining into the fundamental processes that drive carbon capture and storage, such as photosynthesis, litter

fall and decomposition, and root exudation, we can gain a deeper understanding of the intricate mechanisms that contribute to carbon sequestration in various ecosystems.

2. Method of the Review

After selecting the review topic, relevant publications were collected from databases such as Scopus, Web of Science, and Google Scholar using multiple search terms, including *soil organic carbon sequestration*, *SOC dynamics*, *carbon storage*, and related keywords. The initial search yielded a large number of articles up to 2024, which were filtered based on relevance to the study's objectives. In total, 120 articles were retrieved, and after screening titles and after reviewing titles, abstracts, and full texts, 101 articles were selected for further analysis. Of these, 70% were sourced from Google Scholar, and 30% from Web of Science and Science Direct.

3. Discussion

3.1. Soil Organic Carbon

Soil organic matter (SOM), a collection of diverse organic compounds present in soils, is the main source of organic carbon (C). It includes all organic materials living and non-living at all stages of decomposition [8]. Soil organic carbon (SOC), a major component of SOM, consists of microbial biomass and byproducts, as well as plant and animal residues at different decomposition stages. SOC is a heterogeneous mixture of simple sugars, complex organic compounds, inert elements, fresh litter, and carbohydrates. Globally, soils store about 1,550 Pg (1 Pg = 10¹⁵ g) of organic carbon within the top one meter roughly twice the amount in the atmosphere (780 Pg) and 2.5 times that in the biotic pool (620 Pg) [9]. Historical land conversion for agriculture has caused significant carbon losses, estimated at 78 Pg globally 26 Pg through erosion and 52 Pg through mineralization [10]. Converting native woodland and grassland to cropland reduces SOC stocks by about 42% and 59%, respectively [11].

Enhancing soil carbon storage is therefore considered a key strategy to mitigate atmospheric CO₂ [10]. Higher soil carbon levels also improve soil quality, agronomic productivity, and water quality [12]. Conservation agriculture practices, including crop and residue management as well as organic farming, can enhance SOC sequestration [13]. Long-term experiments, such as the Rothamsted Classical Trials, demonstrate that continuous applications of 35 t ha⁻¹ of farmyard manure (FYM) since the 1840s increased soil carbon from 1% to 3.5%. Similarly, at Woburn, annual FYM applications of 37.5 t ha⁻¹ raised soil carbon from 0.87% to 1.64% between 1942 and 1967, and doubling FYM further increased it to 2.26% [12]. These historic losses and subsequent gains highlight the substantial potential of agricultural soils to re-sequester large amounts of atmospheric CO₂ and restore SOC to near pre-

clearing levels.

3.2. SOC in the Ethiopia Situation

Ethiopia’s tropical climate and mountainous terrain create wide variations in rainfall and temperature. Annual rainfall ranges. from about 100 mm in the northeastern lowlands of Afar to 2,400 mm in the southwestern highlands, mainly influenced by elevation and prevailing wind systems from the Indian Ocean [14, 15]. These climatic and topographic differences, along with diverse parent materials and vegetation, have resulted in 19 major soil types, including Lithosols (14.7%), Nitosols (13.5%), Regosols (12.0%), Cambisols (11.1%), and Vertisols (10%). Similarly, vegetation distribution is shaped by soil type, climate, and topography, giving

rise to four major biomes: savanna, mountain vegetation, tropical thickets and forested steppe, and desert steppe vegetation [14].

The Ethiopian highlands, characterized by steep and undulating terrain, support dense populations and intensive land use. Land conversion from forest to cropland has caused significant soil organic carbon (SOC) losses estimated at 5.4 Mg C ha⁻¹ following deforestation, compared to sequestration rates of 1–3.2 Mg ha⁻¹ yr⁻¹ in forest soils [16]. Overall, SOC losses from erosion, deforestation, and land-use change in Ethiopia are estimated to range from 15 to 1,000 kg ha⁻¹ yr⁻¹ [11] with forest and woodland conversion being the primary drivers of soil organic matter decline.

Table 1. Changes of SOC and some properties of soils in different locations of Ethiopia. Source: [11].

Soil Site	order	pH (H ₂ O) Vegetation	Texture	OC (g kg ⁻¹)			
				Forested	Cultivated	Forested	Cultivated
Awassa	Andisol	High land savanna	LS	5.28	5.45	40.3	16.6
Ghinch	Vertisol	Savanna	C	5.74	5.98	32.8	20
Holeta	Vertisol	Savanna	C	5.58	4.88	36.1	16
Jimma	Alfisol	Rain forest	C	6.15	4.94	47.3	20.2
Sirinka	Vertisol	Guinea savanna	C	6.02	6.75	27.2	7.7

According to [17], the predominant soil types in Ethiopia’s highlands are Nitosols, Ferralsols, and Vertisols, with large areas covered by Vertisols that contain 3–10% organic matter, increasing with higher clay content. Cambisols are found in both highlands and lowlands, especially on eroded slopes, while soils in dry lowland areas are typically shallow and low in organic carbon Highland soils generally have higher organic matter due to greater vegetation cover, deeper profiles, and cooler temperatures. Recognizing the role of soil carbon sequestration, the Ethiopian government has implemented several initiatives such as the National Soil Policy, the National Action Program to Combat Desertification, the Climate-Resilient Green Economy Strategy, and the Growth and Transformation Plan to promote land rehabilitation and sustainable management. About 16.4% of Ethiopia’s total land area is protected as nature reserves and national parks [18], which function as carbon sinks by conserving vegetation and soil carbon and preventing deforestation, a major source of greenhouse gas emissions.

3.3. Soil Organic Carbon Fractions

One reliable measure of the health of the soil is soil organic

carbon. A key element of soil quality and the source of many ecosystem services is the SOC pool, which includes its quantity, depth distribution, turnover, and mean residence time [8]. According to [19], the primary cause of the SOC growth was thought to be the biomass-C input, and the rise in SOC stocks was directly correlated with the gains of labile SOC fractions. SOC fractions are vital in sustaining soil quality and are indicators of different management strategies.’ Total organic carbon (TOC), particulate organic carbon (POC), microbial biomass carbon (MBC), dissolved organic carbon (DOC), permanganate oxidizable carbon (KMnO₄-C), and mineral associated organic carbon (MOC) are some of the pools and fractions that make up the SOC [20].

3.3.1. Total Organic Carbon (TOC)

According to [20], the carbon fraction in soil organic matter (SOM) represents total organic carbon (TOC), with SOM containing about 58% carbon. SOM consists of materials varying in size and decomposability, classified into three main soil organic carbon (SOC) pools: active, slow, and passive. The active pool includes fresh residues and microbial products with a turnover time of 1–10 years, while the slow pool, associated with stable aggregates, decomposes over 10–100 years. The

passive pool, or resistant SOM, is highly stable and decomposes over more than 100 years due to its association with fine mineral. TOC is commonly determined through chemical oxidation, either by removing inorganic carbon using acid treatment or by fully oxidizing all carbon in the sample to CO₂ for quantification [21].

3.3.2. Particulate and Mineral-associated Organic Carbon

The three main categories of SOM that are typically classified by physical fractionation techniques are: mineral-associated organic matter (MinOM; size <53 µm), fine particulate organic matter (fPOM), and coarse particulate organic matter (cPOM), which contains organic pieces larger than 250 µm [20]. According to the findings, finer POM fractions seemed to be more degraded based on isotope and C:N ratios, whereas coarse sediments had more C and N content. Furthermore, with rising event runoff came contributions from humus and forest floor litter to cPOM, and litter contributions rose with higher rainfall intensities [15].

3.3.3. Mineral-associated Organic Carbon

Organic carbon that is physically linked to soil minerals either by occlusion inside aggregates or adsorption to reactive surfaces is referred to as mineral-associated organic carbon, or MAC. According to [22], MAC is regarded as a slow-cycling pool of SOC since it has a longer mean residence time (MRT) than other SOC pools. Traditionally, the persistence of MAC has been attributed to the physical protection provided by soil minerals.

3.3.4. Dissolved Organic Carbon (DOC)

The term "DOC" describes the portion of organic carbon in solution that makes it past a 0.45 µm filter. It is an essential component of the dynamics of soil organic matter and has a big impact on a lot of different biogeochemical processes in both terrestrial and aquatic settings. DOC is a mobile and dynamically cycling portion of organic matter that affects biogeochemical processes in soil and water systems. It impacts various processes, including global warming, contamination of water and soil, and drinking water quality [20].

3.3.5. Extractable Organic Carbon

The function of extractable organic carbon in microbial interactions and soil organic carbon dynamics is what makes it unique. It plays a crucial role in the conflict between microbial absorption of dissolved organic carbon (DOC) and sorption to minerals. Consequently, the active participation of extractable organic carbon in microbial processes and its impact on the persistence of soil organic carbon define it [22].

3.3.6. Soil Microbial Biomass Carbon

Soil Microbial Biomass Carbon is referred to as MBC. According to [23], it refers to the living mass of organic matter in the soil, which includes bacteria, fungi, algae, protozoa, and other soil microfauna. Temperature, precipitation, altitude, soil depth, and seasonal variations are some of the variables that affect the stock of soil microbial biomass carbon (MBC) in forest ecosystems. The mean annual temperature (MAT) and MBC stock exhibit a favorable association. Increased MBC storage is correlated with higher temperatures and lower elevations but inverse relationship with higher precipitation levels [20, 23].

3.4. Soil Organic Carbon (SOC) Sequestration Mechanisms

Soil carbon sequestration is the result of biotic and abiotic processes that transfer atmospheric CO₂ into soil organic matter (SOM) through photosynthesis and subsequent decomposition [1]. Soil biota from microorganisms to arthropods play a central role by mediating carbon inputs and mineralization, maintaining a dynamic equilibrium that determines SOC levels. Climatic factors such as rainfall, temperature, and oxygen availability influence both plant productivity and microbial activity, while soil properties like clay content, mineralogy, and structure affect organic matter stabilization. Through photosynthesis, carbon fixed in plant biomass is transferred to the soil as roots, litter, and residues decompose under the influence of soil organisms [1]. Abiotic factors such as mineral composition, moisture, and temperature alongside biotic activities together regulate SOC sequestration, making understanding these mechanisms essential for improving soil carbon storage and climate resilience.

Carbon Inputs

Organic carbon (OC) enters the soil mainly through litter, crop residues, and rhizodeposition, with plant biomass being the largest contributor [24]. Litter and crop residues contribute OC via leaching of soluble compounds, while rhizodeposition releases low molecular weight compounds from roots. Terrestrial, phytobenthos-, and phytoplankton-derived carbon also contribute, though at varying degrees [25]. Long-term OC storage in soils is influenced by these inputs and their transformation by soil microbes and interaction with minerals [26].

Agricultural management practices (AMPs) can enhance soil organic carbon (SOC) sequestration and mitigate climate change by increasing carbon inputs and reducing SOC losses [27]. Strategies include cover crops, no-till farming, organic amendments, agroforestry, nutrient management, and water conservation [28, 29]. Cover crops, for example, can significantly increase SOC stocks while maintaining yields [25, 30]. Other measures, such as promoting perennials, organic farming, and zero tillage, also improve long-term carbon storage and soil health [31].

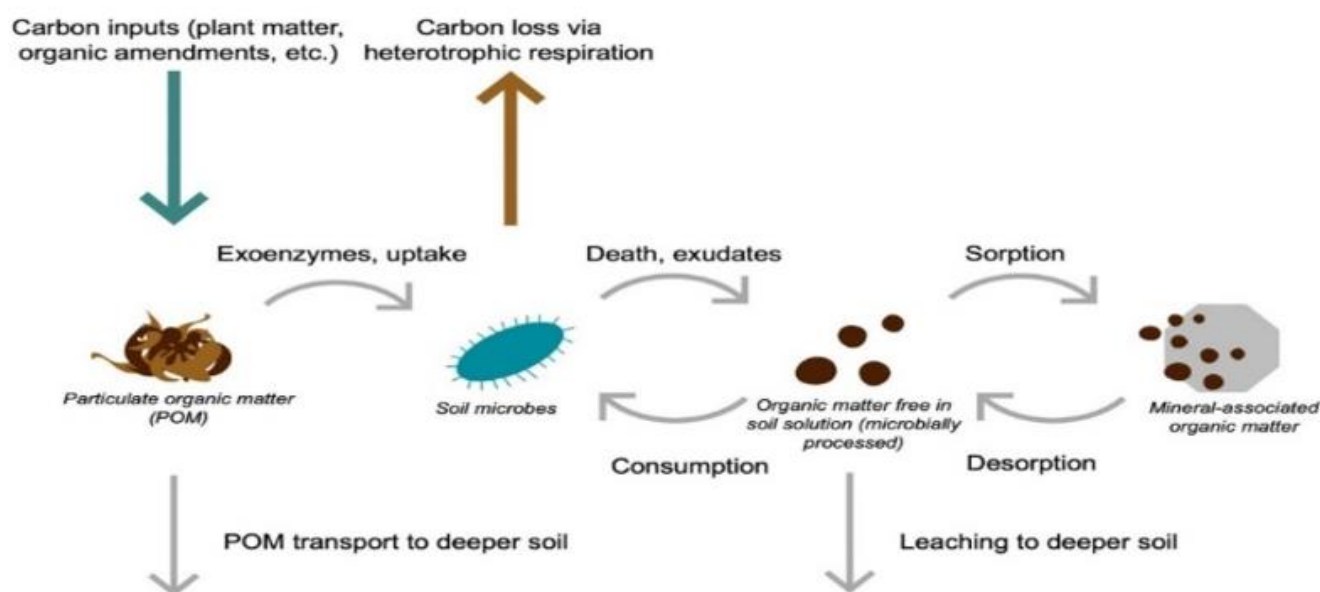


Figure 1. Conceptual illustration of soil carbon (C) flows. Carbon is mostly taken up by plants (green arrow) and expelled from the soil by heterotrophic respiration (brown arrow). Particulate organic matter (POM) comes from plant carbon inputs and can move deeper into the soil or be broken down by microbes into biomass. Mineral-associated organic matter (MAOM) forms when microbially processed carbon binds to minerals, which can then leach deeper or be reabsorbed by microbes, gradually transferring both POM and MAOM to deeper soil layers. Source [26].

3.5. Mechanisms of Soil Organic Carbon Stabilization (Protection)

The main processes that allow soils to store carbon include protection inside soil aggregates, the movement of dissolved organic carbon (DOC) into subsurface, the interaction of SOC with clay fractions, bioturbation, and the creation of secondary (pedogenic) carbonates [32]. Physical, chemical, and biological protection mechanisms, as well as their combinations, can be used to categorize the several suggested methods of carbon sequestration and stability in soils [32].

3.5.1. Physical Protection and Stabilization Mechanisms

Soil organic carbon (SOC) is stabilized through strong chemical bonds with minerals and physical protection that limits microbial access [32, 33]. This includes adsorption onto clay surfaces, occlusion in aggregates, and interactions with metal ions and minerals, which prevent microbial degradation and extend SOC persistence [10]. Reactive soil minerals, especially clays, play a key role in SOC retention by providing surfaces for bonding and enhancing stability [34]. In Andosols,

stable micro aggregates, Al–humus complexes, and low microbial activity contribute to SOC protection. Repeated tephra deposition and the presence of aluminium, allophane, and possibly iron further stabilize SOC by shielding it from decomposition. These mechanisms collectively enhance the long-term storage of carbon in soils [35–37].

3.5.2. Chemical Protection and Stabilization Mechanisms

Soil organic matter (SOM) is chemically protected through the formation of recalcitrant compounds, such as black carbon from fires, humic substances, lipids, and chitin, which are resistant to decomposition [32, 35, 36]. These compounds, derived from plants, soil organisms, and fire, have complex structures that enhance stability, making black carbon one of the most persistent forms of soil carbon due to its highly aromatic and condensed nature [38].

3.5.3. Biological Protection Mechanisms

These mechanisms involve the encapsulation of SOC in soil aggregate formation and hydrophobic domains of soil organic matter, protecting its accessibility to degrading soil micro-organisms and their enzymes [32].

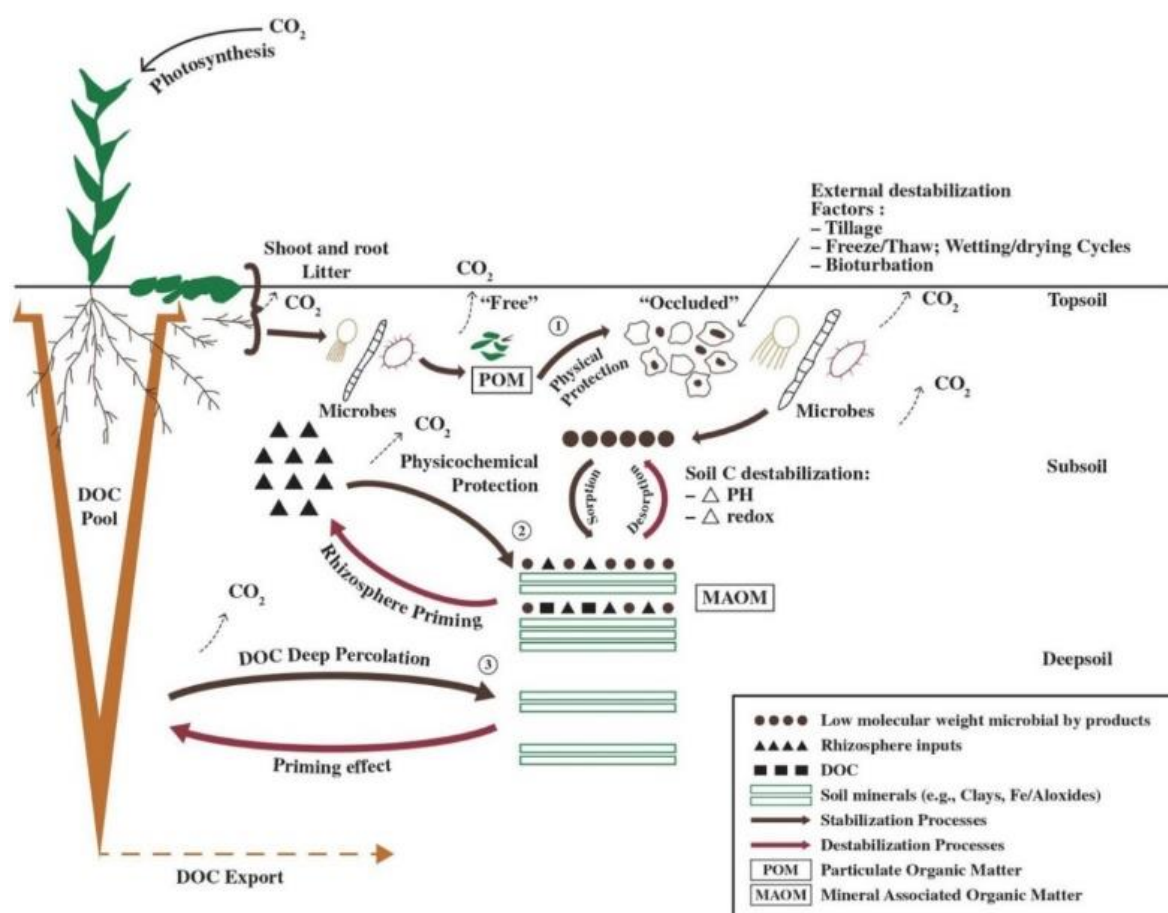


Figure 2. Summary of the main mechanisms of soil organic carbon stabilization Source: [39].

4. Management Practices to Increase SOC (Sequestration) in Cropland

The net balance of organic C inputs and losses is reflected in SOC. Thus, soil C storage can be increased by agricultural management techniques that enhance C inputs by raising crop yield, applying external sources of C (such as animal manure, compost, and biosolids), and/or decreasing C losses. Effective management techniques that generally boost SOC storage include: managing crop yields; tillage and crop residue management; crop rotation; managing pasture and grazing; adding organic matter; and using alternative farming systems [40].

4.1. Conservation Tillage and Crop Residue Retention

Conservation tillage practices, such as direct drill, no-till, and minimum tillage, combined with crop residue retention, are effective for reducing soil erosion, conserving moisture, and enhancing soil organic carbon (SOC), particularly in the upper soil layers [13]. Studies have shown that switching from conventional tillage to no-tillage can increase SOC in the top 20 cm of soil, with reported gains ranging from 0.03 to 1.95

Mg C ha⁻¹ yr⁻¹, depending on climate and soil type [41].

Long-term research highlights that most SOC accumulation under no-tillage occurs in the top 10–15 cm, with negligible changes or even decreases at deeper layers. For example, a 28-year no-tillage site showed higher particulate organic carbon in the surface 5 cm than a 4-year site, but overall SOC differences between the two durations were minimal. These results indicate that sampling depth and soil layer considerations are crucial when assessing SOC changes under conservation tillage [42].

4.2. Compost

Composting converts organic waste into nutrient-rich compost that improves soil structure, water retention, and fertility. Compost provides organic matter that fuels microbial activity, promoting the formation of stable soil organic carbon [43] and capturing carbon derived from atmospheric CO₂ [44, 45]. It gradually releases essential nutrients, enhancing plant growth and reducing reliance on synthetic fertilizers. Compost also supports diverse microbial communities and overall ecosystem health while reducing water runoff and erosion [46]. To optimize SOC storage, high-quality compost should be applied appropriately, and soil carbon levels should be regularly monitored [47].

4.3. Biochar

Biochar, produced via pyrolysis of organic materials, is a stable form of carbon with a long soil residence time. When applied to soil, it acts as a carbon sink, enhancing SOC storage and mitigating climate change [48]. Biochar can accumulate additional organic matter from plant residues, root exudates, and microbial biomass, further increasing carbon sequestration [49]. It reduces carbon losses via erosion and microbial decomposition by improving soil structure, stability, and microbial community composition. Its porous structure supports beneficial microbes that enhance nutrient cycling and incorporate carbon into stable SOC pools [50, 51]. Biochar also improves soil health, water retention, nutrient availability, and plant productivity, indirectly promoting further carbon accumulation. The effectiveness of biochar in increasing SOC depends on feedstock, production conditions, soil type, climate, and management practices, making proper application and monitoring essential [45, 51, 52].

4.4. Pasture Management Practices

Pasture management strongly affects soil organic carbon (SOC) dynamics. Pastures have higher root-to-shoot ratios and lower disturbance, promoting greater SOC accumulation than intensively managed croplands [53]. Practices like fertilization can further increase SOC, with nitrogen and sulfur additions raising SOC by 0.5–1.0 Mg C ha⁻¹ yr⁻¹ over 5–13 years. Grazing intensity also matters, as moderately grazed pastures often have higher SOC than heavily grazed ones. The choice of species influences SOC, with perennial grasses enhancing storage due to deeper roots [54, 55].

4.5. Irrigated Systems

Irrigated systems are vital for crop production in arid and semi-arid regions, often doubling biomass compared to rain-fed crops. Irrigation increases carbon inputs to soil via enhanced plant residues and roots, boosting SOC sequestration rates from 222 to 969 kg C ha⁻¹ yr⁻¹ [56, 57]. In the western U.S., SOC gains from irrigation range from 0.25 to 0.52 Mg C ha⁻¹ yr⁻¹, and irrigation increases SOC in pastures and conservation tillage systems relative to native ecosystems. Expansion of irrigated agriculture can further enhance SOC storage, potentially sequestering ~8.0 Mg C ha⁻¹ through land-use shifts. Actual SOC gains depend on climate, soil type, irrigation management, crop rotation, tillage, and cover crop use [56].

5. Factors Affecting Soil Organic Carbon (Soc) Storage

Factors affecting soil organic carbon (SOC) storage, also

known as sequestration, are diverse and encompass various aspects of the soil-plant system and management practices. Some of the key factors influencing SOC storage are.

5.1. Plant Inputs

SOC originates from atmospheric carbon dioxide (CO₂) captured by plants through photosynthesis. The amount of SOC is influenced by the quantity and quality of plant biomass inputs. Factors such as plant productivity, species composition, and vegetation cover can affect the amount of carbon transferred to the soil through root biomass, aboveground residues, and exudates [58].

5.2. Climate

Rainfall and temperature are primary climatic factors that influence plant productivity and subsequent decomposition rates of SOC. In natural ecosystems, these factors determine the equilibrium SOC level. Different climatic conditions can impact the balance between carbon inputs and losses, thus affecting SOC storage [59].

5.3. Land Use and Management Practices

Land use and management practices play a crucial role in SOC storage. Agricultural systems, for example, are subject to specific management practices that can impact SOC turnover rates and equilibrium levels. Tillage practices, crop rotation, organic amendments, and residue management practices all influence the amount of carbon input, decomposition rates, and erosion risks, ultimately affecting SOC storage [20].

5.4. Erosion

Soil erosion can result in the loss of SOC from agro ecosystems [6]. Eroded soil particles often contain significant amounts of organic matter. The fate of eroded soil determines whether it acts as a net sink or source. Implementing erosion control measures, such as conservation tillage or contour farming, can help reduce SOC losses associated with erosion.

5.5. Soil Properties

Soil depth and type strongly influence soil organic carbon (SOC). SOC generally decreases with depth due to higher root and residue inputs and greater microbial activity in the topsoil [60], though in some soils like vertisols, shrink-swell dynamics can move organic matter downward, increasing deep SOC [61]. SOC also varies by soil type: Histosols, rich in organic matter, have the highest SOC, often in wetlands, while Aridosols in arid regions have the lowest [62].

Table 2. SOC level varies among soil types.

Soil Order (US Taxonomy)	SOC (Pg) (10^{15} g)	SOC (t/ha)
Alfisols	127	7.0
Andisols	78	31
Aridosols	110	4.0
Entisols	148	10
Histosols	357	205
Inceptisols	352	16
Mollisols	72	13
Oxisols	119	10
Spodosols	71	15
Ultisols	105	9.0
Vertisols	19	6.0

Source: [63]

Soil texture, defined by the proportions of sand, silt, and clay, strongly influences soil organic carbon (SOC) storage [64]. Sandy soils, with larger particles and lower surface area, decompose organic matter faster, while clay soils, with smaller particles and higher surface area, protect SOC through physical and chemical mechanisms [65]. Multivalent cations (Ca, Al, Fe) in clay minerals form complexes with organic matter, enhancing SOC stability and contributing to soil aggregation. Understanding soil texture SOC relationships aids in predicting SOC dynamics and guiding management strategies.

5.6. Composition of Soil Minerals

Soil mineral composition strongly affects organic carbon (C) storage, turnover, and soil–atmosphere carbon fluxes. Multivalent cations (Ca^{2+} , Al^{3+} , Fe^{3+}) stabilize organic matter through adsorption and complexation, reducing microbial degradation. Clay minerals and soil organic matter contribute to cation exchange capacity (CEC), enhancing the soil's ability to retain carbon [60, 66]. Greater mineral surface area increases binding sites for organic carbon, promoting formation of stable mineral–organic complexes [67].

5.7. Soil pH

Soil pH, reflecting hydrogen ion activity, strongly affects microbial activity, enzyme efficiency, and organic matter decomposition. Enzymes have optimal pH ranges, with near-neutral soils (pH 6.5–7.5) showing highest decomposition rates [68]. Extreme pH values reduce microbial enzymatic activity, slowing decomposition. In natural ecosystems, lower

pH can increase soil organic carbon (SOC) by enhancing organic matter adsorption and reducing microbial decomposition [69, 70].

6. Factors Limiting SOC Sequestration

Soils that have greater SOM under management practices such as reduced tillage, residue incorporation, and N fertilization can function as a C sink and a nutrient reservoir for soil biota. Increasing C storage in soils has important ecosystem benefits, but there are indications that there is a limit to a soil's capacity to store SOC [59, 71].

6.1. Carbon Saturation

Soil organic carbon (SOC) does not always increase linearly with higher carbon inputs, limiting the efficiency of carbon stabilization. Carbon saturation occurs when a soil reaches its maximum SOC storage, where carbon inputs equal losses, so further additions do not significantly raise SOC found that once clay and silt adsorption limits are reached, extra organic matter does not increase sequestration. SOC is finite, approaching a new equilibrium over time, and long-term studies show it does not accumulate indefinitely [72, 73].

6.2. Non-permanence

Soil carbon (C) storage is not permanent, as changes in land use or agricultural practices can reduce soil carbon. For example, carbon gained during a grass or legume ley can be partly lost when plowed into arable land, though long-term ley-arable rotations usually increase soil organic carbon (SOC) com-

pared to continuous arable cropping. Carbon loss from management changes occurs faster than accumulation, and even at equilibrium, carbon additions are needed to maintain soil C levels [74-76].

7. Conclusion

Soil organic carbon (SOC) sequestration is vital for mitigating climate change by capturing atmospheric CO₂ and storing it in soils. Processes like photosynthesis, litter decomposition, and root exudation, along with physical, chemical, and biological stabilization mechanisms, enhance SOC accumulation. Practices such as no-till farming, cover cropping, and organic amendments can increase SOC, improve soil fertility and water retention, and support sustainable land management. However, SOC loss from erosion, deforestation, and land-use change in Ethiopia (15–1000 kg ha⁻¹ yr⁻¹) highlights gaps in implementing national carbon sequestration policies.

Abbreviations

AMP	Agricultural Management Practices
DOC	Dissolved Organic Carbon
MBC	Microbial Biomass Carbon
MRT	Mean Residence Time
POC	Particulate Organic Carbon
TOC	Total Organic Carbon
FYM	Farmyard Manure
MAC	Mineral-Associated Organic Carbon
MAT	Mean Annual Temperature
MRT	Mean Residence Time
PG	Penta Gram
POM	Particulate Organic Matter
SOC	Soil Organic Carbon
SOM	Soil Organic Matter

Author Contributions

Tesfaye Tadesse Gebre: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing

Amanuel Jorge: Data curation, Formal analysis, Investigation, Writing – original draft

Conflicts of Interest

The authors declare no conflicts of interest.

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