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Review

Soil carbon sequestration: Nature's way to fight climate change

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Abstract

Soil carbon sequestration is a natural and effective mechanism for mitigating climate change by capturing and storing atmospheric carbon dioxide in soil organic matter. Healthy soils act as major carbon sinks through processes such as plant residue decomposition, root biomass accumulation and microbial activity. Sustainable land-use practices (including conservation tillage, crop rotation, cover cropping, agroforestry and organic amendments) enhance soil carbon storage while improving soil fertility, water retention and biodiversity. By strengthening ecosystem resilience and supporting sustainable agriculture, soil carbon sequestration offers a cost-effective, nature-based solution to reduce greenhouse gas concentrations and combat the adverse impacts of climate change.

Keywords: Soil carbon sequestration, Climate change mitigation, Soil organic carbon, Sustainable agriculture and Nature-based solutions.

Introduction

The sustainability of the earth is currently at risk due to impending climate change. The impacts of climate change are already being felt around the world, with extreme weather events, rising sea levels, and melting glaciers [1]. India is ranked as the 5th most vulnerable country to the adverse impacts of climate change [2]. The primary driver of climate change is the rising global temperature due to global warming. In the latest IPCC synthesis report by Lee [3], it is noted that a temperature increases of 1.10 C, driven by human activities, has triggered climate changes unprecedented in recent human history. The report also suggests that there are over 50% chance that global temperatures will rise by at least 1.50 C between 2021 and 2040. Under a high-emissions scenario, however, this threshold could be reached even earlier, potentially between 2018 and 2037. This temperature increase could lead to serious and irreversible impacts on ecosystems, human health, and food production. The report further warns that climate change could seriously threaten the achievement of the Sustainable Development Goals (SDGs).

Increasing CO2 levels in the atmosphere is a major factor in causing climate change, so strategies that reduce CO2 levels need to be implemented to mitigate its effects. One possible solution to mitigate climate change and slow down global warming is the sequestration of carbon through soil. Soils are the largest reservoir of carbon (C), containing over 70% of the terrestrial organic C [4]. This amount is larger than the combined organic carbon mass stored in living biomass and the atmosphere [5]. Thus, soil organic carbon (SOC) plays a crucial role in the global carbon cycle. Depletion of the SOC pool generally results in higher atmospheric CO2 concentration and diminished soil quality, serving as major contributors to global warming and land degradation, respectively [6]. On the other hand, SOC sequestration represents a promising approach to mitigating global warming and promoting sustainable agriculture. It is therefore imperative

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to better understand SOC dynamics and its influencing factors is essential for improved carbon management, helping to alleviate the concurrent challenges of climate change and food scarcity [7].

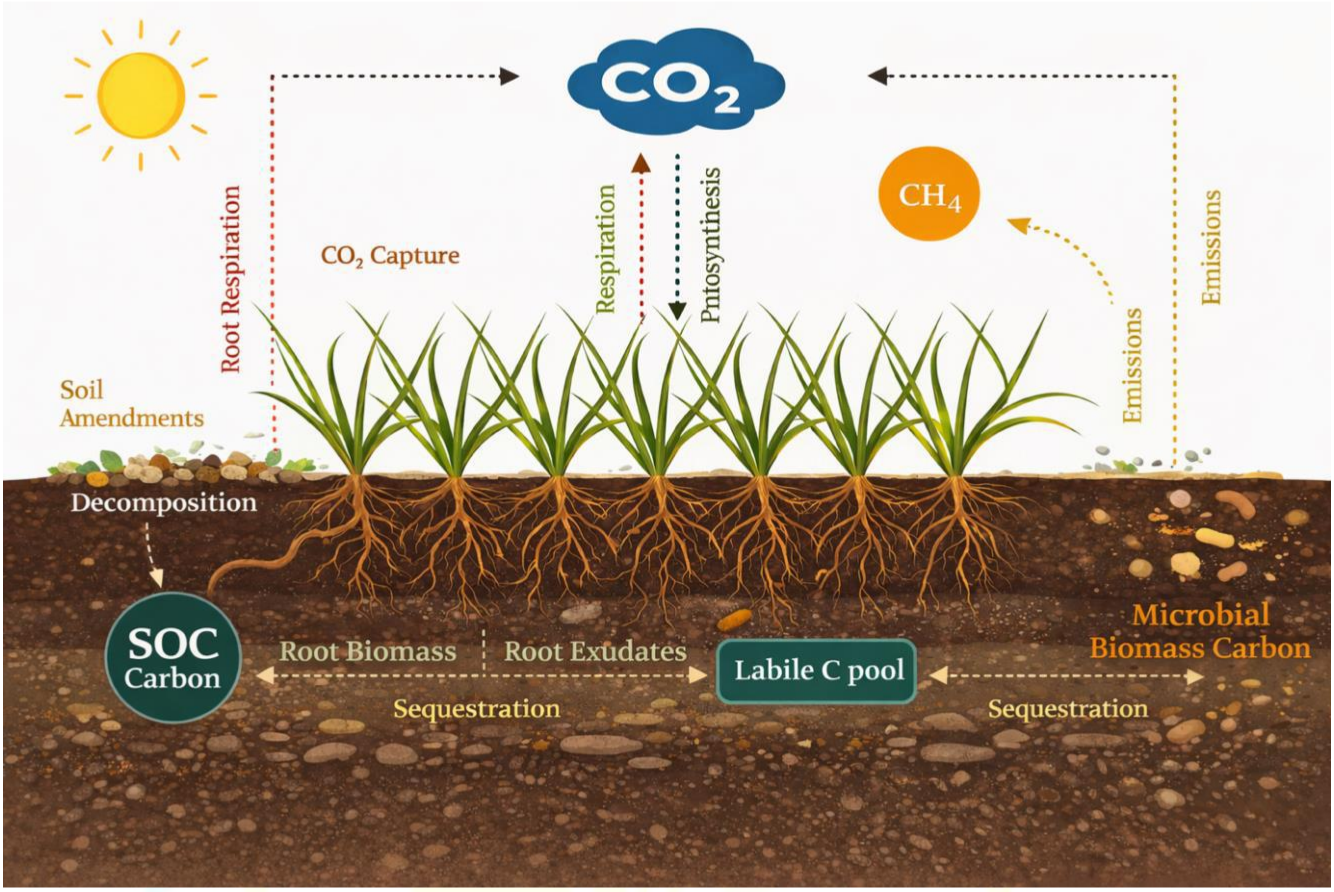

Fig. 1. Schematic diagram representing CO_2 emissions and soil carbon sequestration

Role of Soil in the Global Carbon Cycle

Soils constitute the largest terrestrial carbon reservoir, storing approximately 2,500 gigatons (Gt) of carbon, which is more than three times the amount contained in the atmosphere and nearly four times that in terrestrial vegetation. This carbon exists in both organic and inorganic forms, with soil organic carbon (SOC) being the most dynamic and biologically active pool. The SOC stock is influenced by the balance between carbon inputs (derived from plant residues, root exudates, and organic amendments) and carbon losses through decomposition, erosion and leaching. Thus, managing soils to increase SOC levels presents a significant opportunity to remove CO_2 from the atmosphere and store it in a stable form over extended timescales.

Soil Organic Carbon

Highly essential factor in regulating and sustaining the physical, chemical, and biological activities of soil is SOC which is also a significant indicator of soil health. Conceptually SOC can be defined as leftover remains of plant and animal origin with different stages of decomposition and of microbial biomass along with their decomposition by-products [8]. Being highly reactive, it can influence several physico-chemical, biological, ecosystem and pedogenic processes which ultimately affect soil quality [9]. There is a wide range of organic carbon pools in soil, ranging from readily decomposable to highly recalcitrant fractions that maintain soil quality as well as serve as sensitive indicators of soil management practices that are important for crop productivity. These pools vary in their chemical composition, decomposition rate and role in soil health and function. Based on the length of time carbon remains undecomposed, measured by "mean residence time" and soil carbon is categorized into three different pools such as active pool, slow pool and passive pool.

a) Active SOC pool: It is a labile form of C, comprising fresh plant and animal residues. This pool is linked to soil biological processes. The labile C pool with the most rapid decomposition within a few days to a few years. This pool supplies energy to soil microbes, facilitating nutrient cycling and improving soil quality and productivity.

b) Slow SOC pool: It is composed of moderately processed plant residues and microbial by-products of the labile C pool. This C pool has physical protection against microbial and biological decomposition. The mean residence time of the slow C pool ranges from years to decades and can be influenced by soil type, management practices, and climate conditions.

c) Stable SOC pool: This pool comprises of humus or non-labile form of C and is not biologically active. It is related to C sequestration and climate change. Stable C pool has mean residence times ranging from centuries to millennia because of its strong resistance to any change.

Maintaining soil carbon status is fundamental to the sustainability of any production system. Therefore, to determine the impact of soil organic carbon on environmental change more accurately, it is necessary to separate SOC into different fractions. The SOC is divided into two fractions- labile organic carbon (LOC) and recalcitrant organic carbon [10]. Organic carbon pool serves as an energy source for microbes and facilitates nutrient cycling to increase productivity. According to various studies, the labile carbon pool has been identified as one of the most sensitive fractions of soil organic carbon. This fraction can be used to assess soil quality and fertility changes on both a short-term and long-term basis [11]. Conversely, passive pools or recalcitrant pools are altered very slowly by microbial activity, so they are poorly suitable for assessing soil quality and productivity [10]. The passive or recalcitrant pools contribute significantly to carbon sequestration.

Concept of Soil Carbon Sequestration

Soil carbon sequestration refers to the process of capturing atmospheric CO_2 and storing it in the soil in the form of organic matter. Soil carbon sequestration is a win-win strategy that enhances food production while improving soil quality [12].

Approximately 1700 Gt of carbon is found in the top 1 m of soil, which is twice the amount found in the atmosphere, four times the amount found in vegetation and 160 times as much as the current annual anthropogenic CO_2 emission rate [13]. Therefore, even a minor alteration in SOC can have a significant impact on the global carbon budget. The SOC budget reflects the equilibrium between organic carbon inputs and losses through various pathways [14]. Storage of C in deeper soil layers is an alternative strategy to reduce CO_2 concentrations in the atmosphere, which contributes to climate change mitigation. The key methods for increasing SOC storage include: (1) increasing the application of organic matter to soils, (2) slowing the decomposition of organic matter to promote long-term SOC retention, and (3) providing mechanical protection to SOC by improving the stability of soil aggregates and organo-mineral complexes [15].

Mechanisms of SOC Sequestration

In a soil ecosystem, and within soil horizon, multiple mechanisms can function simultaneously to stabilize soil organic carbon. The three main mechanisms by which soil carbon can be stabilized are Physical stability of SOC, Chemical stability of SOC and Biochemical stability of SOC.

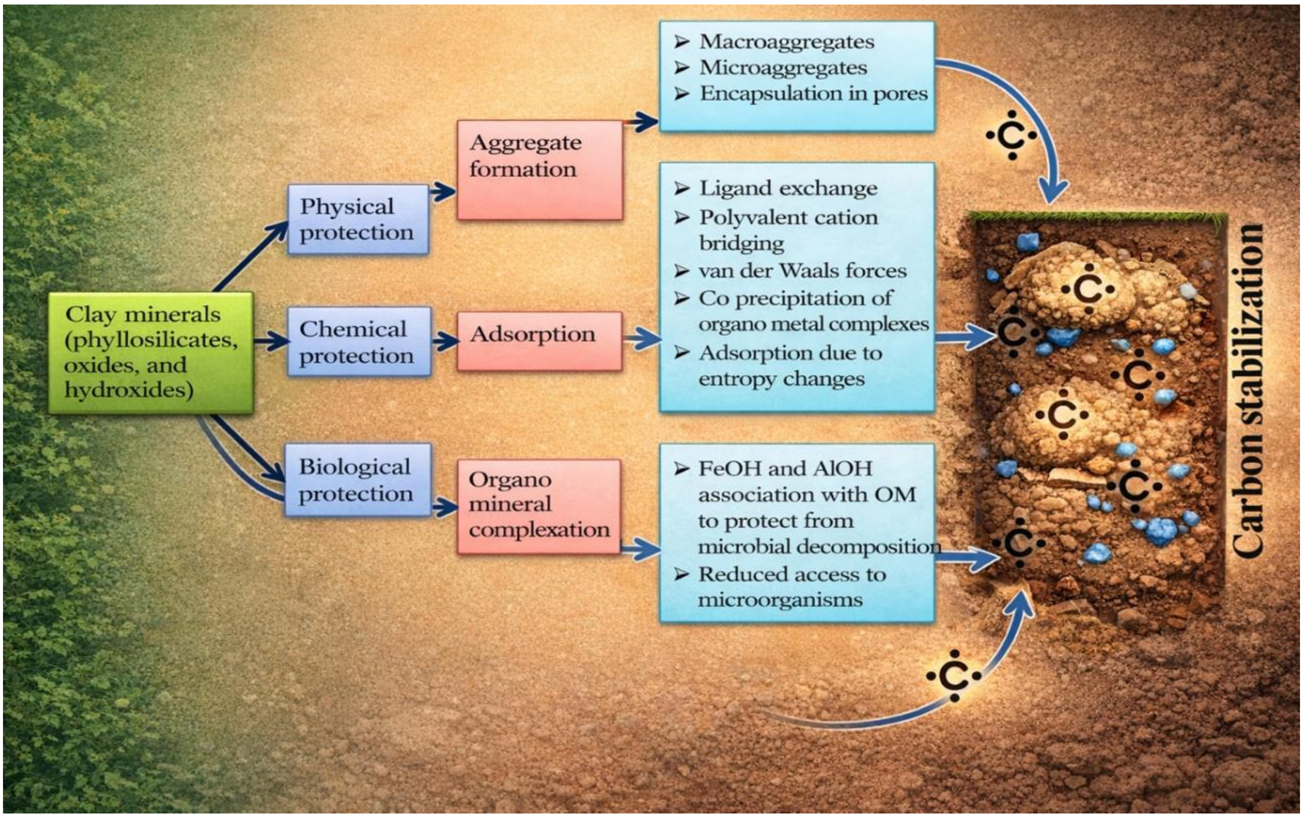

Fig. 2. Schematic diagram of stabilization mechanism of SOC

Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularized in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum.

Management practices for enhancing soil carbon sequestration

Several land management and agronomic practices have been identified as effective strategies for enhancing SOC sequestration. The success of these approaches depends on their compatibility with local agroecological conditions and their ability to promote carbon inputs while minimizing carbon losses.

Conservation and Reduced Tillage: Minimizing soil disturbance through no-till or reduced-till practices reduces the exposure of soil organic matter to oxidation and erosion. Conservation tillage fosters greater residue retention, improved soil aggregation, and increased microbial biomass, leading to higher carbon stabilization in the soil profile.

Cover Cropping and Crop Residue Management: The inclusion of cover crops such as legumes and grasses during fallow periods adds organic matter to the soil, enhances root biomass, and protects against erosion. Retaining crop residues instead of burning them ensures a continuous supply of organic inputs, thus improving SOC content over time.

Table 1. Soil carbon sequestration under different management practices

Management Practice	Potential SOC Increase (Mg C ha^{-1} yr^{-1})	References
Conservation tillage / No-till	~0.1–0.5	[12]
Cover cropping	~0.2 -0.8	[16]
Organic manure and compost application	~0.2–0.6	[17]
Agroforestry systems	~1.4	[18]
Integrated nutrient management (INM)	~1.23	[19]
Biochar amendment	~0.37 – 0.56	[20]

Organic Amendments and Manure Application: Application of organic manures, compost, green manures, and crop residues enhances the quantity and quality of carbon inputs. These amendments increase microbial activity, nutrient cycling, and the formation of stable humic substances that contribute to long-term carbon storage.

Agroforestry and Afforestation: Integrating trees and shrubs with crops and livestock systems increases carbon inputs through leaf litter and root turnover. Agroforestry not only sequesters carbon in soils but also in above-ground biomass, providing a dual carbon sink and improving landscape sustainability.

Biochar Application: Biochar, a carbon-rich by-product of biomass pyrolysis, has emerged as a promising amendment for long-term carbon sequestration. It is resistant to microbial decomposition and enhances soil nutrient retention, cation exchange capacity, and water availability.

Integrated Nutrient and Water Management: Balanced nutrient management through the combined use of organic and inorganic fertilizers optimizes plant productivity and enhances root biomass. Proper irrigation management also prevents decomposition losses and improves carbon stabilization under anaerobic microenvironments.

Climate change mitigation through soil carbon sequestration strategies

Climate change, marked by persistent alterations in temperature, precipitation, and weather patterns, has emerged as a major concern over the past century. Human activities such as fossil fuel combustion, rapid industrialization, and deforestation are the primary drivers, producing excessive greenhouse gases, especially CO_2, which trap heat and raise global temperatures [21]. These changes pose a serious global challenge, affecting ecosystems, agriculture, and food security [22]. Fossil fuel use and land-use changes have raised atmospheric CO_2 levels by roughly 31% globally, highlighting the need for effective mitigation measures [23]. Since the Industrial Revolution, soil cultivation and fossil fuel combustion have contributed approximately 136 Pg and 270 Pg of carbon, respectively, to global emissions. Additionally, activities like deforestation, conversion of natural ecosystems to agriculture, biomass burning, wetland drainage, and soil cultivation have released around 78 Pg of carbon from the SOC pool [6]. Consequently, some agricultural soils have lost between half to two-thirds of their native SOC, emphasizing the critical need for restorative practices. Among various mitigation options, soil carbon sequestration has emerged as an effective and sustainable strategy for reducing atmospheric CO_2 concentrations. Soils act as a major terrestrial carbon sink, containing nearly three times more carbon than the atmosphere, primarily in the form of soil organic carbon. The process of soil carbon sequestration involves capturing atmospheric CO_2 through plant photosynthesis and storing it as stable organic matter within soil aggregates. Enhancing SOC stocks contributes not only to climate change mitigation but also to improved soil fertility, structure, and water retention. Various management practices (such as conservation tillage, cover cropping, residue retention, agroforestry, organic manure application, and biochar incorporation) play crucial roles in increasing SOC levels. These practices enhance carbon inputs through root biomass and organic amendments while minimizing carbon losses via erosion and mineralization. Furthermore, integrated nutrient and water management supports microbial activity and humus formation, promoting long-term carbon stabilization. These strategies, when applied effectively, have the potential to sequester 0.9 Pg of SOC annually, which could offset one-quarter to one-third of the predicted 3.3 Pg y^{-1} yearly increase in atmospheric CO_2. Over 25–50 years, soil carbon sequestration can store 30–60 Pg C naturally [12]. Beyond rehabilitating degraded soil, effective soil carbon sequestration strategies can increase biomass output, improve groundwater quality, and help balance CO_2 emissions from fossil fuels by reducing the overall emissions to the atmosphere [24]. However, the extent of SOC sequestration potential is influenced by soil characteristics, climatic conditions, and the intensity of land management. For large-scale adoption, supportive policies, carbon credit mechanisms, and sustainable land management frameworks are essential. Integrating soil carbon sequestration strategies into national climate action plans can play a pivotal role in meeting global climate mitigation targets while ensuring soil health and agricultural productivity. Therefore, soil carbon sequestration serves as a vital nature-based solution that concurrently mitigates climate change, strengthens ecosystem resilience, and supports sustainable agricultural development.

Challenges and Limitations

Despite its potential, soil carbon sequestration is not without challenges. The amount of carbon soils can store depends on climate, soil type, vegetation, and management practices. Carbon gains can be reversed if land use changes or soils are disturbed again. Additionally, measuring and verifying changes in soil carbon is complex and requires advanced monitoring systems. Therefore, while it is an effective tool, it must be part of a wider strategy that includes emissions reduction and renewable energy use.

Global Efforts and Policy Support

Several International initiatives recognize the importance of soil in combating climate change. The "4 per 1000" initiative, launched at the 2015 Paris Climate Conference, encourages countries to increase global soil carbon stocks by 0.4% per year-an amount that could offset much of the world's annual CO_2 emissions. Governments and organizations are also promoting carbon farming and carbon credit markets, which reward farmers for adopting sustainable soil management practices.

Conclusion

Soil carbon sequestration represents a natural, cost-effective, and sustainable strategy to combat climate change. By capturing atmospheric CO_2 and storing it in soils, it not only helps mitigate global warming but also improves soil health, fertility, and water retention, supporting sustainable agriculture and ecosystem resilience. While there are limitations, such as soil carbon saturation and climatic variability, adopting practices like conservation tillage, crop rotation, cover cropping, and organic amendments can significantly enhance soil carbon stocks. Ultimately, utilizing soils as carbon sinks offers a win-win solution, mitigating climate change while supporting food security, environmental sustainability, and the conservation of biodiversity.

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