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Exploring soil organic and inorganic carbon dynamics for carbon sequestration potential of cotton cultivation

A. Manikandan*, D. Blaise, A.S. Tayade and Y.G. Prasad

ICAR-Central Institute for Cotton Research, Nagpur- 440010, Maharashtra, India

Abstract : Cotton has a net negative carbon footprint, making it a significant contributor to carbon sequestration efforts. From 1960 to 2020, atmospheric CO_2 level rose by 100 ppm, reaching 418 ppm. Cotton captures 2.2 kg of carbon and emits 1.7 kg of greenhouse gases for every kilogram of fibre, showing its potential for carbon offset. India's extensive 12.5 million hectares of cotton cultivation offer substantial soil carbon sequestration potential, primarily through the storage of soil organic carbon (SOC) and soil inorganic carbon (SIC), both of which are essential for mitigating climate change and supporting agro-ecosystem health. SOC and SIC storage occur via distinct processes that lock carbon in the soil in various forms. Cotton regions provide 3-5 Mg ha^{-1} of stalks annually, contributing 4-6 g kg^{-1} of SOC upon soil incorporation. Organic carbon is essential in the upper 0.3 m soil layer, while inorganic carbon (IC), prevalent at depths of 0.3 -1.0 m, is especially relevant in rainfed cotton regions, where calcification and secondary carbonate formation make IC a notable carbon sink (more than 63% of IC in these areas). However, IC dynamics remain underexplored despite their stability and contribution to soil resilience. SIC processes involve bicarbonate (HCO_3^-) movements, potentially sequestering carbon through carbonate crystallisation, yet are susceptible to CO_2 release if exposed by erosion. SIC also supports soil fertility, water retention, and crop yield, thereby enhancing ecosystem services, including provisioning, regulation, cultural, and supporting roles. However, irrigation combined with nitrogen and sulphur fertilisers may destabilise IC, leading to CO_2 emissions through carbonate precipitation. In dry regions, calcification predominates, slowing CO_2 release from soils. Understanding these processes, especially at greater soil depths, is crucial for managing soils in cotton-growing areas to achieve sustainable carbon sequestration and ecosystem resilience.

Keywords: *Carbon sequestration, Inorganic carbon, Organic carbon, Rainfed cotton*

Introduction

Carbon sequestration is the process of capturing and storing carbon dioxide (CO_2) from the atmosphere over the long term to reduce greenhouse gas concentrations and mitigate climate change. It is a critical strategy in the fight against global warming, as it helps to prevent CO_2 from being released into the atmosphere, where it would otherwise contribute to the greenhouse effect. However, carbon sequestration should complement-not replace-efforts to reduce greenhouse gas emissions at the source. A balanced approach that combines emission reduction with enhanced carbon sequestration is essential for effective climate change mitigation (Wang *et al.,* 2019).

Natural methods of carbon sequestration include forests, oceans, and soils, where CO_2 is absorbed and stored in organic matter or through soil carbon processes. Soil, in particular, plays a significant role as it captures

***Corresponding author**: (Email: poonamani223@gmail.com)

carbon through the decomposition of organic materials, converting them into stable soil organic carbon (SOC), which can remain in the soil for long periods (Wang et al., 2019) (Fig. 1). Artificial methods also contribute to sequestration efforts and include Carbon Capture and Storage (CCS), Direct Air Capture (DAC), Enhanced Weathering, and projects like afforestation and reforestation, which increase vegetation cover to capture CO_2. By integrating these natural and artificial strategies, a more sustainable pathway can be achieved to reduce atmospheric CO_2 level.

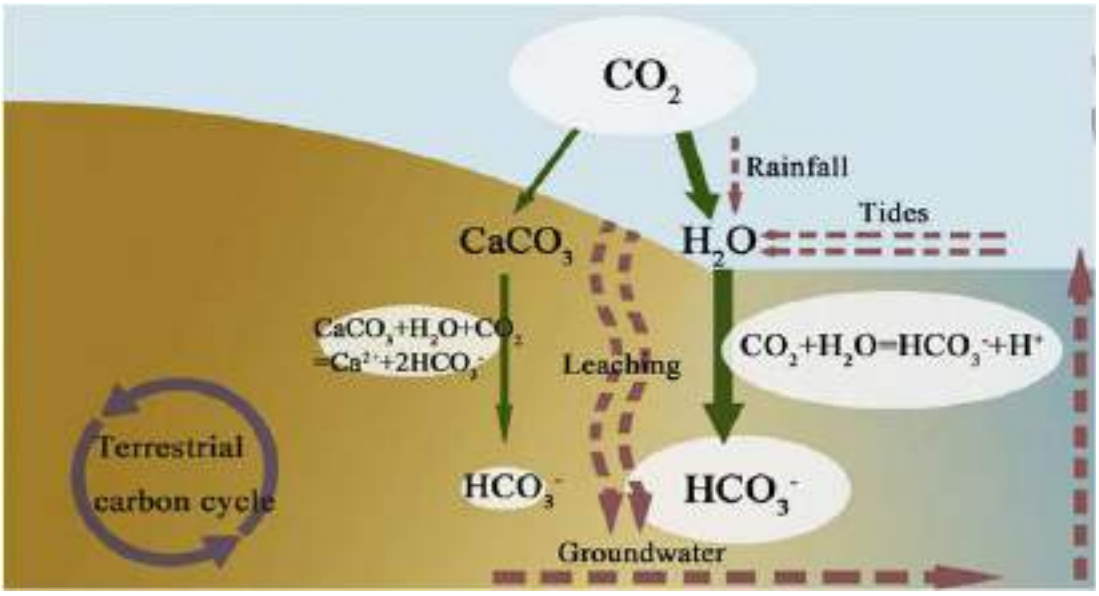

Fig. 1: Pathways for soil carbon sequestration (adopted from Wang et al., 2019)

From 1960 to 2020, atmospheric Co_2 level surged by around 100 ppm, from 280 to 418 ppm, reflecting a significant increase in greenhouse gases (Fig. 2). Cotton, a C3 plant known for its cellulose-rich fibres, sequesters 2.2 kg of carbon while emitting 1.7 kg of greenhouse gases per kilogram of fibre, making it both a contributor and a mitigator in CO_2 dynamics. In India, cotton cultivation spans 12.5 million hectares across diverse soil types, including black, calcareous, red and laterite, coastal alluvial, and saline-alkali soils, across three main regions - North, South, and Central India (Table 1). Despite more than 63% of cotton farms being rainfed, they exhibit substantial carbon sequestration potential.

Globally, cotton farms emit 15.5 million tonnes of carbon annually, but, according to the International Cotton Advisory Committee (ICAC), they capture about 99.8 million tonnes of carbon, translating to an average of 3,022 kg of carbon sequestered per hectare (Kranthi, 2023). Indian cotton soils alone capture an estimated 32 million tonnes of carbon yearly. Carbon storage occurs in both plant biomass and soil, with soil storing three times more carbon than plants and animals combined. In cotton systems, Soil Organic Carbon (SOC) is stabilized through practices like residue incorporation, reduced tillage, precision farming, and biochar amendments (Velmourougane *et al.,* 2022). Soil Inorganic Carbon (SIC) processes, such as calcium carbonate precipitation, silicate weathering, formation of dissolved inorganic carbon (DIC), CO_2 absorption, and interactions with soil alkalinity, also play crucial roles. These combined mechanisms enable cotton-growing soils to act as significant carbon sinks, underscoring the essential role of SOC and SIC in sustaining carbon storage and mitigating atmospheric CO_2.

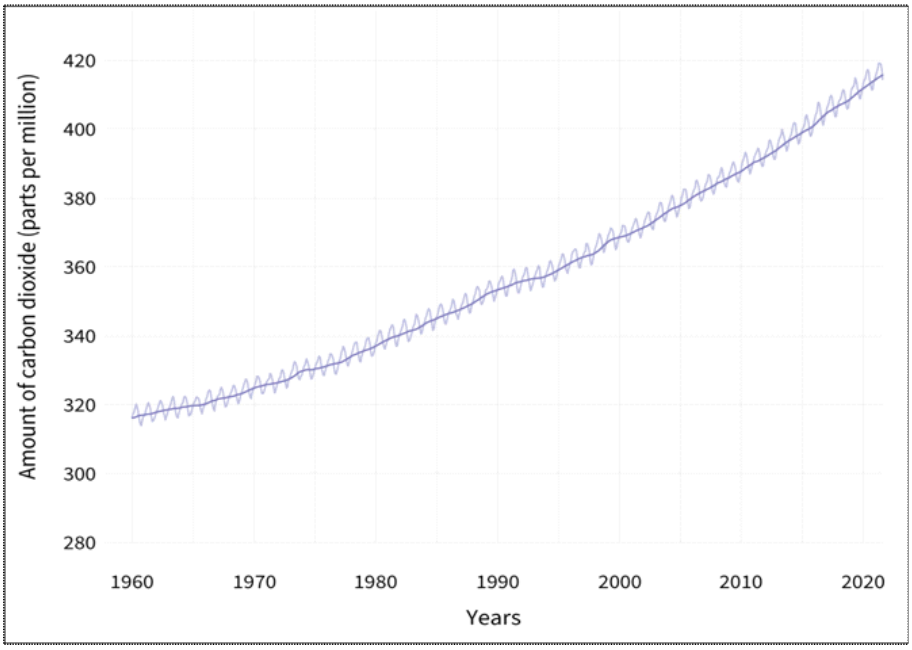

Fig. 2: Temporal trend of atmospheric carbon dioxide (ppm) for the last six decades

Table 1: Carbon sequestration potential of cotton growing states of India

States/UTs	Area (lakh ha)	Release of Carbon (lakh ton)	Capture of Carbon (lakh ton)
Andhra Pradesh	5.69	2.7	17.2
Gujarat	26.82	12.6	81.1
Haryana	6.65	3.1	20.1
Karnataka	6.86	3.2	20.7
Madhya Pradesh	6.5	3.1	19.6
Maharashtra	42.22	19.8	127.6
Odisha	2.3	1.1	7.0
Punjab	1.69	0.8	5.1
Rajasthan	7.91	3.7	23.9
Tamil Nadu	0.68	0.3	2.05
Telangana	18.13	8.5	54.8
Others	0.1	0.05	0.3
India	125.55	59.01	379.41

Soil Carbon

Soil carbon refers to the carbon stored in soils, primarily as soil organic carbon (SOC) and soil inorganic carbon (SIC). SOC, derived from decomposed plant materials and roots, is added to soils through plant photosynthesis, while SIC is stored as calcium carbonate ($CaCO_3$) formed through pedogenic processes (PC). Both SOC and SIC are critical for ecosystem functions, as they affect soil fertility, water-holding capacity, and various soil properties.

Globally, soil carbon plays a vital role in the carbon cycle and contributes to mitigating atmospheric greenhouse gases (GHGs), especially CO_2. SOC helps improve soil structure and nutrient availability, which

benefits plant growth, while SIC stabilises soils in arid and semi-arid regions. Together, these forms of soil carbon not only support agro-ecosystems but also contribute to the broader effort to manage CO_2 level and combat climate change by acting as significant carbon sinks.

Organic *vs* Inorganic Carbon Sequestration

Soil Organic Carbon (SOC) and Soil Inorganic Carbon (SIC) sequestration represent two distinct pathways for storing carbon in soils, each with unique mechanisms and benefits for climate change mitigation. SOC sequestration occurs through the incorporation of decomposed plant materials and roots into the soil, where carbon is stored in stable organic matter over time. This process enhances soil fertility, improves soil structure, and supports water retention, benefiting crop productivity and ecosystem health.

In contrast, SIC sequestration involves the storage of carbon in mineral forms, primarily as calcium carbonates ($CaCO_3$), through processes such as pedogenic carbonate formation. SIC sequestration is particularly significant in arid and semi-arid regions, where calcification naturally occurs and stabilizes soils. While SIC contributes less to soil fertility than SOC, it provides long-term carbon storage due to the stability of mineral carbonates, which remain in the soil for centuries or even millennia.

Both SOC and SIC sequestration are crucial for effective carbon management strategies. SOC is often faster to accumulate and directly enhances soil quality, making it vital for agroecosystems (Table 2). SIC, though slower to form, offers enduring carbon storage and resilience in specific soil types. Together, balancing SOC and SIC sequestration can contribute to a more comprehensive, sustainable approach to reducing atmospheric CO_2 level and addressing climate change.

Table 2: Comparison of Organic *vs*. Inorganic carbon sequestration

Process	**Organic**	**Inorganic**
Nature of Carbon Storage	Involves the storage of carbon in organic compounds. This typically occurs in living or once - living organisms, such as plants, trees, and soil organic matter.	Involves the storage of carbon in mineral forms, such as carbonates. This process is often associated with geological formations like rocks, minerals, and sediments.
Processes	The uptake of atmospheric CO_2 by photosynthetic organisms, such as plants and trees. This captured carbon is stored in the form of organic molecules through photosynthesis.	Often rely on geological and chemical processes. For example, minerals like olivine or basalt can react with atmospheric CO_2 through a process called mine ral weathering, forming stable carbonates.
Mechanisms	Forests play a crucial role in organic carbon sequestration. Trees absorb CO_2 during photosynthesis, converting it into organic biomass. Soil organic carbon sequestration also occurs through the decomposition of plant and animal matter.	Carbon Capture and Storage (CCS) is a prominent example of inorganic carbon sequestration. It in volves capturing CO_2 emissions from industrial sources and storing them in geological formations like depleted oil and gas reservoirs or deep saline aquifers.

Time Scales	Processes can vary in time scales. For example, the carbon stored in living plant biomass may be released relatively quickly if the plants die and decompose, while soil organic carbon can persist for longer periods.	Long-term geological processes. The storage of carbon in mineral forms can remain stable over geological time scales.
Applications	It is applied in various natural and sustainable practices; including afforestation, reforestation, and agricultural practices that enhance soil organic carbon.	CCS are often applied to capture and store emissions from industrial sources.

Soil Organic Carbon (SOC)

Soil Organic Carbon (SOC) is composed of various organic matter forms within the soil, including plant residues, animal remains, microbial biomass, and humus. SOC plays a fundamental role in soil fertility, water retention, nutrient cycling, and soil structure. It can be classified into several types based on composition, origin, and stability.

Plant Residues: In cotton-growing soils, SOC originates from plant residues such as leaves, burs, branches, stalks, roots, and other plant debris (flowers, bolls, seeds, lint) that decompose in the soil. Annually, cotton residues contribute 3-5 and 5-7 tons per hectare to SOC through fresh organic matter added to the soil surface and then incorporated into the soil profile (Silanikove and Levanon, 1986). Although 38 to 63 million tons of cotton stalks are generated annually in Indian cotton soils, these residues are rarely managed scientifically (Velmourougane *et al.,* 2022). The carbon sequestered from these residues is categorised as a "fast pool," with a degradation period ranging from days to months. Incorporating cotton residues in soil accelerates their decomposition (taking 6-7 months) and enhances nutrient availability.

Microbial Biomass: This form of SOC consists of carbon stored in living soil microorganisms, including bacteria, fungi, and actinomycetes. Microbial Biomass Carbon (MBC) is a dynamic soil organic carbon (SOC) pool, as microbes assimilate and release carbon through growth and metabolic processes. In cotton-based cropping systems, MBC has been recorded at 128 µg g^{-1} in rainfed soils and 650 µg g^{-1} in irrigated soils (Velmourougane *et al.*, 2014; 2022).

Humus: Humus is an amorphous, stable organic substance formed from the breakdown of plant and microbial residues, containing 58% carbon. It represents a long-lasting SOC fraction that improves soil aggregation, water retention, nutrient cycling, and cation exchange capacity. In a 96-year monocropping experiment on cotton, Meylikovich et al. (2022) observed varying humus consumption based on agricultural treatments (Table 3). The study included three treatments: control (0.059 kg of humus per 1 kg of cotton produced), application of 30 tons of manure per hectare with 25 kg of phosphorus per hectare (0.108 kg), and an NPK fertiliser treatment (250:175:125 kg per hectare) resulting in 0.206 kg. This SOC is considered a "medium pool," with degradation occurring over the years.

Table 3: Changes in the amount of humus (in 0-30 cm layer) and cotton yield in fields with long-term permanent cultivation of cotton (Meylikovich et al., 2022)

	The initial amount of humus in (1926)			After 96 years (2022)				
Treatments	%	t/ha	Cotton yield (t/ha)	%	t/ha	Cotton yield (t/ha)	Total gross yield of 96 years	Humus amount for 1 kg of cotton (kg)
Every year 30 t/ha manure+ 25 kg/ha P_2O_5	1.84	68.45	-	0.96	32.5	32.7	306.8	0.108
NPK 250:175:125 kg/ha	1.42	53.25	-	0.87	16.6	33.9	330.4	0.059
Without fertilizer (Control)	1.42	53.25	-	0.64	29.1	9.9	141.0	0.206

Charcoal (Biochar): Cotton stalks are hardwood with slow decomposition due to high lignin content, so they are often converted to biochar (16-23%). Biochar, a stable form of charcoal produced by pyrolysis of organic materials, resists microbial degradation and acts as a long-term carbon sink while enhancing soil fertility and structure. This "slow pool" of carbon persists for hundreds of years. Shi et al. (2020) found that a decade of biochar application (4.5 and 9 Mg ha^{-1} annually) increased soil inorganic carbon (0.4 Mg C ha^{-1}), soil organic carbon (9 Mg C ha^{-1}), and total carbon stocks (12 Mg C ha^{-1}) in the 0-15 cm soil depth.

Dissolved Organic Carbon (DOC): DOC consists of soluble organic compounds in soil solution from organic matter decomposition, root exudates, and microbial activity, aiding in nutrient cycling, microbial function, and plant nutrition. DOC levels in farmland soils range from 61 to 1266 mg kg^{-1} (Smreczak and Ukalsha-Jaruga, 2021). Table 4 shows the DOC share in the soil organic matter of farmland soils.

Table 4: Examples of dissolved organic matter share in soil organic matter of soils from farmland (Smreczak and Ukalsha-Jaruga, 2021)

Site	Soil layer (cm)	Other information	TOC (g/kg)	DOC (mg/kg)	%
Cropland	0-15	Maize monoculture manured	34.4	1226	3.56
		Maize monoculture	25.3	674	2.66
		no amendment	29.2	801	2.74
Forest cropland	0-30	-	38.4	731	1.90
		-	12.0	150	1.25
Cropland	0-30	Phaeozems	7.65	62.8	0.82
		Luvisols	7.24	61.3	0.85
Agriculture areas	0-20	Soil monitoring system of Hungary	22.0	100.9	0.46
Cropland	0-10	Soil without amendments	5.98	120.3	2.01
		Soil with sewage and sludge at 30 t/ha	5.83	127.3	2.18
		Soil with sewage and sludge at 30 t/ha	6.12	145.3	2.37

Particulate Organic Matter (POM): POM includes visible organic particles such as plant debris and microbial biomass, which are less decomposed than humus and contribute to labile carbon sources for nutrient cycling and microbial activity. Shi et al. (2020) showed that biochar application (4.5 and 9 Mg ha^{-1} annually for ten years) increased POM by 38-166% at 0-15 cm depth compared to untreated soils. Fig. 3. Indicates the POC along with other types of soil carbon.

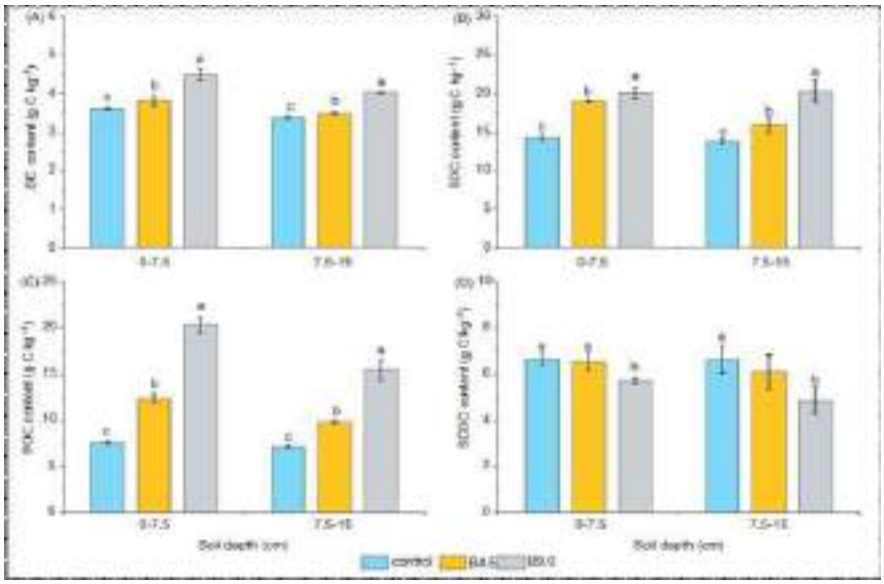

Fig. 3: Soil inorganic carbon, soil organic carbon, particulate organic carbon, and silt-clay associated organic carbon fraction

Stabilised Organic Carbon: SOC that is physically or chemically protected within soil aggregates or mineral complexes, making it resistant to decomposition, is classified as stabilised carbon. This form of SOC supports long-term carbon storage and soil fertility, with soil aggregates and hydrophobic domains protecting SOC from microbial degradation (Goh, 2004). Fig. 4 indicates the mechanisms of carbon stabilisation in soils by clay-minerals.

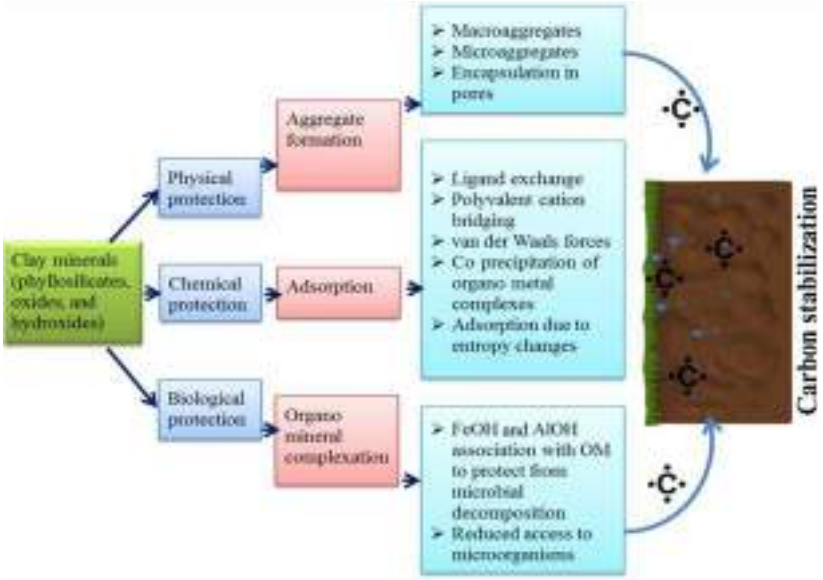

Fig. 4: Mechanisms of carbon stabilization in soils by clay-minerals (Adopted from Singh et al., 2018)

Understanding the dynamics and interactions of these SOC types, particularly in the surface layer (0-0.3 m), is crucial for evaluating soil carbon stocks, nutrient cycling, soil health, and the potential of soils to capture atmospheric carbon, contributing to climate change mitigation (Singh et al., 2018).

Soil Inorganic Carbon (SIC)

Soil Inorganic Carbon (SIC) encompasses carbon compounds that lack carbon-hydrogen (C-H) bonds, often found in mineral forms associated with geological and soil processes. Unlike soil organic carbon (SOC), which primarily originates from decomposed plant and animal residues, SIC is stored in the form of carbonates and other minerals. This makes SIC a stable, long-term form of carbon storage, especially in soils with calcareous (high-calcium) characteristics. Global soil carbon stocks contain approximately 2500 giga tons (Gt) of carbon within the top 2 meters, with a substantial portion in the form of inorganic carbon (Eswaran et al., 2000). Monger et al. (2015) describe the "generation concept," noting that SIC sequestration occurs primarily in the "first generation" stage, when calcium is released directly from silicates, initiating the process of carbonate mineral formation.

SIC contributes to the carbon cycle through its stability in soil environments, especially in semi-arid and arid regions. This sequestration process is essential for climate change mitigation because SIC remains in the soil for extended periods, effectively reducing atmospheric CO_2 level without undergoing rapid decomposition like SOC. Various forms of SIC, such as carbonate minerals and dissolved inorganic carbon, contribute to soil stability, structure, and productivity. Here's an in-depth look at the different forms and mechanisms of SIC.

Carbonate Minerals and Their Role in SIC

Calcite ($CaCO_3$): Calcite is one of the most abundant carbonate minerals and is primarily found in sedimentary rocks like limestone, marble, and chalk. It plays a crucial role in carbon sequestration through mineral weathering, where calcium released from calcite combines with CO_2 to form stable carbonates. In India's cotton-growing regions, calcareous soils under rainfed conditions encourage the formation of stable soil aggregates, which, in turn, enhance water infiltration, soil structure, and productivity. The presence of calcite contributes to the long-term storage of carbon in these soils by creating a stable environment that minimises carbon release.

Dolomite ($CaMg(CO_3)$: Another significant carbonate mineral, dolomite is a composite of calcium and magnesium carbonates, often occurring in sedimentary formations. Like calcite, dolomite can sequester carbon through mineral weathering. Recent studies by Guo et al. (2023) indicate that applying calcium and magnesium-rich silicate rock powder at a rate of 10 kg/m² to agricultural soils can accelerate carbon sequestration and productivity. For instance, this practice has been shown to boost crop yield by 7% and biomass by 11%, while sequestering around 4.31 tons of CO_2 per hectare annually. Furthermore, it enhances carbon stability by approximately 20% and results in a net carbon capture rate that is 1.6-2.4 times higher than regional averages in China.

Dissolved Inorganic Carbon (DIC): Bicarbonate and Carbonate Ions

Dissolved Inorganic Carbon (DIC) refers to carbon stored as bicarbonate (HCO_3) and carbonate (CO_3) ions in natural water bodies. These ions form when CO_2 dissolves in water, eventually reacting to form carbonic acid (H_2CO_3) and subsequently bicarbonate and carbonate ions. This process enables carbon to be stored in water and soil as part of the deeper soil layers and groundwater systems. Together, SIC in the form of soil carbonates (~940 petagrams of carbon, PgC) and DIC in groundwater (~1404 PgC) constitute the largest terrestrial carbon pool, surpassing even soil organic carbon, which is estimated at around 1530 PgC globally (Monger et al., 2015).

This form of SIC is particularly relevant in arid and semi-arid regions, where water availability is limited, and carbonate formations occur naturally. The carbonate and bicarbonate ions remain dissolved in groundwater or

soil water, effectively serving as a carbon sink. Their stability prevents quick release into the atmosphere, offering long-term storage that complements the rapid cycling of organic carbon in more temperate regions.

Carbon Dioxide (CO_2) - Gaseous CO_2 in Soil Processes

Though CO_2 is typically a gas, it can dissolve in water and contribute to SIC through interactions with water molecules, forming carbonic acid (H_2CO_3). This weak acid subsequently dissociates to form bicarbonate and carbonate ions, which are further stored in soils as stable forms of inorganic carbon. In coastal wetlands, for example, the leaching and absorption of CO_2 are the predominant mechanisms of SIC sequestration. This process is instrumental in maintaining the carbon balance in these sensitive ecosystems, as discussed by Wang et al. (2019).

The interaction between CO_2 and soil is highly significant for maintaining soil structure and fertility. When CO_2 dissolves in soil water and becomes part of the inorganic carbon pool, it can contribute to mineral weathering and the formation of calcium and magnesium carbonates, thereby sequestering carbon in stable, long-lasting forms. This process is particularly beneficial in regions with high rates of CO_2 release due to decomposition, as it helps balance the carbon inputs and outputs within the soil.

Alkalinity in Natural Waters and Its Role in SIC

Alkalinity measures the ability of water to neutralize acids and is associated with the presence of bicarbonate, carbonate, and hydroxide ions. In agricultural and natural systems, alkaline soils can contain substantial amounts of SIC in the form of carbonates. The precipitation of secondary carbonates is a primary mechanism by which SIC sequesters carbon in alkaline soils. These secondary carbonates, which form when calcium ions react with CO_2 in the soil solution, provide a stable form of carbon storage that is less prone to microbial decomposition (Rashid *et al.*, 2019).

Alkalinity is particularly beneficial in arid and semi-arid regions, where evaporation rates are high, and bicarbonate and carbonate ions tend to accumulate. These ions increase soil pH, reduce the solubility of CO_2, and enhance carbonate precipitation, contributing to carbon sequestration over extended time scales. Alkaline soils with high SIC content are generally stable and contribute to long-term carbon storage, thereby supporting sustainable agricultural practices in regions prone to soil degradation and desertification.

Mechanisms of SIC Formation and Stabilisation

SIC is primarily stabilized through processes such as mineral weathering, leaching, and carbonate precipitation. These processes contribute to the long-term sequestration of carbon in soil and prevent its rapid release back into the atmosphere:

1. **Mineral Weathering:** When primary minerals like calcium and magnesium silicates are weathered, they release calcium and magnesium ions, which react with CO_2 to form stable carbonate minerals. This process can be enhanced by adding silicate rock powders to agricultural soils, promoting mineral dissolution and increasing carbon capture, as demonstrated by Guo *et al.* (2023).
2. **Leaching of CO_2 :** In areas where soil moisture levels are adequate, CO_2 can dissolve into soil water and leach into deeper soil layers, where it forms bicarbonate ions. This leaching process allows SIC to move downward into more stable soil horizons, where it remains less susceptible to release.
3. **Precipitation of Secondary Carbonates:** In alkaline soils, calcium ions in the soil solution can combine with bicarbonate ions to form secondary carbonates. This form of SIC is stable and persists for long durations, enhancing soil structure and providing a durable form of carbon storage.
4. **Formation of Dissolved Inorganic Carbon (DIC) in Groundwater:** The interaction of CO_2 with soil water can also lead to the formation of bicarbonate ions, which are transported into groundwater as DIC. This process is essential in

areas where water movement is slow, allowing carbon to remain trapped in the soil matrix for extended periods.

5. **Carbonation of Calcium and Magnesium Ions:** Carbonation occurs when calcium or magnesium ions react with dissolved CO_2 , leading to the precipitation of carbonate minerals. This process is especially relevant in regions with high mineral content, where SIC can form naturally over time.

The Role of SIC in Soil Productivity and Environmental Stability

In addition to its function as a carbon sink, SIC contributes to soil productivity and environmental stability. The presence of carbonate minerals improves soil aggregation, water-holding capacity, and nutrient availability. Furthermore, SIC provides buffering capacity in soils, helping to mitigate the effects of acid rain and soil acidification by neutralizing excess hydrogen ions. This buffering capacity is vital for maintaining soil health and supporting sustainable agriculture, particularly in arid and semi-arid regions where soil resources are limited.

Soil Inorganic Carbon (SIC) sequestration is a critical component of the global carbon cycle, offering stable, long-term storage of atmospheric CO_2 in soil minerals and carbonate compounds. Different forms of SIC, including carbonate minerals, dissolved inorganic carbon, and secondary carbonates, contribute to carbon sequestration through complex geological and soil processes. By enhancing soil structure, water retention, and nutrient availability, SIC supports sustainable land management practices and helps mitigate climate change by reducing atmospheric CO_2 levels. Integrating SIC-focused practices, such as the application of silicate rock powders and management of alkaline soils, can further promote carbon storage and improve agricultural productivity.

Atmospheric CO_2 Absorption by Coastal Soil

The quantitative processes of atmospheric CO_2 absorbed by coastal saline-alkali soil during successive leaching cycles can be discussed in terms of several key factors (Fig. 5). These include the soil's physical and chemical properties, the process of leaching, and the role of CO_2 in the soil's carbon dynamics (Wang *et al.*, 2019).

1. Saline-Alkali Soil Characteristics:

Saline-alkali soils are characterized by high concentrations of soluble salts and alkali (sodium carbonate), which affect soil pH, structure, and microbial activity. These soils often have a higher pH (alkaline conditions), which can influence the solubility of CO_2 and its conversion into bicarbonate and carbonate ions in the soil solution.CO_2 absorption is facilitated in soil when CO_2 dissolves in water, forming carbonic acid (H_2CO_3), which dissociates into H^+ and bicarbonate ions. In alkaline soils, CO_2 can form bicarbonate or carbonate ions, but the high pH may limit the solubility of CO_2 compared to more acidic soils.

2. Leaching Process

Leaching involves the removal of soluble salts from the soil through the percolation of water. When saline-alkali soils undergo leaching, the composition of the soil solution changes, which can influence the CO_2 absorption capacity. The successive leaching cycles will dilute the soil's saline content and modify the ionic composition, affecting CO_2 dynamics. During leaching, CO_2 absorbed by the soil may react with dissolved minerals (such as sodium bicarbonate) or with calcium and magnesium ions to form carbonates, which can be precipitated out, thus reducing CO_2 availability in the soil.

3. CO_2 Absorption during Leaching Cycles

First Leaching Cycle: In the initial stage, as water infiltrates the soil, it dilutes the soluble salts, and CO_2 can dissolve in the resulting aqueous phase. However, as the CO_2 dissolves, its concentration in the soil solution increases, promoting more absorption by the soil.

Subsequent Leaching Cycles: With each successive leaching cycle, the soil's chemical environment changes. The ionic composition becomes less saline, which could

reduce the soil's buffering capacity for CO_2, causing a shift in the balance of CO_2 dissolved in the soil. The effectiveness of CO_2 absorption may decrease as the soil becomes less saline, and more CO_2 may be released into the atmosphere. The successive cycles of leaching will likely lead to a gradual reduction in the amount of CO_2 absorbed, as the salt concentrations decrease and the soil becomes less effective at trapping CO_2 due to the altered chemical environment.

4. Soil Carbon Dynamics

The leaching of CO_2 may influence the soil's overall carbon storage. The chemical reactions involving CO_2 in saline-alkali soils can lead to the formation of stable carbonates, which may remain in the soil long-term. This contributes to carbon sequestration. However, the continual leaching may also flush out soluble carbonates or bicarbonates, leading to the release of CO_2 back into the atmosphere, particularly if the leaching continues in the absence of further carbon input.

5. Impact of Soil Microbial Activity

Soil microbes play a critical role in CO_2 absorption and its conversion to other forms. In saline-alkali soils, microbial activity can be limited due to high salt concentrations and alkaline conditions. As leaching reduces these stress factors, microbial populations may become more active, further affecting the soil's carbon dynamics. Increased microbial activity after leaching can result in enhanced CO_2 fixation, but this process may be temporary, depending on the ongoing changes in the soil's ionic composition.

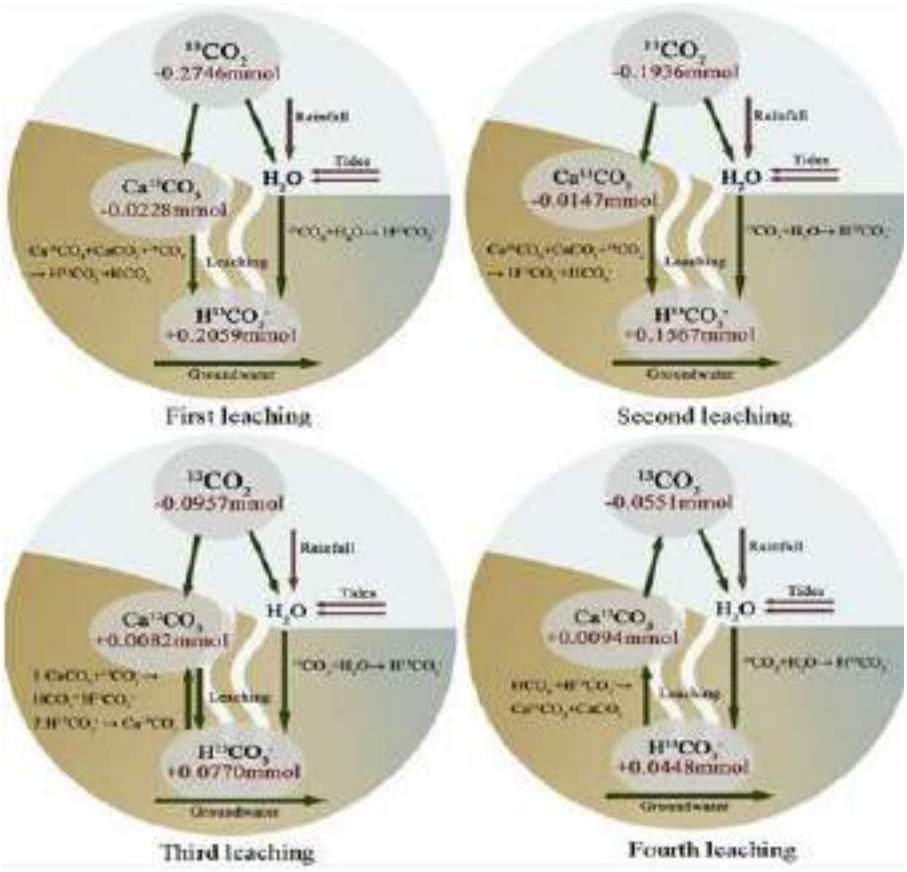

Fig. 5: Quantitative processes of atmospheric CO_2 absorbed by coastal saline-alkali soil during successive four times leaching (Wang et al., 2019)

The absorption of atmospheric CO_2 by coastal saline-alkali soil during successive leaching cycles is a dynamic process influenced by the interaction between soil properties, the leaching process, and microbial activity. The first few leaching cycles may increase CO_2 absorption, but as the salinity decreases and the soil's buffering capacity changes, the absorption may stabilise or even decrease. The overall impact on CO_2 sequestration depends on the duration and intensity of leaching, as well as the changes in the soil's physical and chemical properties over time.

Mineral Weathering Products and Carbon Sequestration

Silicate minerals, like olivine and basalt, are integral to carbon sequestration as they undergo weathering processes that release cations such as calcium and magnesium, which, in turn, interact with carbon dioxide (CO_2) to form stable carbonate minerals. This process not only stabilizes inorganic carbon but also consumes CO_2 , aiding in its long-term removal from the atmosphere. Mineral weathering contributes to the geological carbon cycle by transforming atmospheric CO_2 into solid carbonates, which are then stored within soil and rock formations, effectively sequestering carbon for extended periods.

In the context of carbon capture and storage (CCS), mineral weathering plays a significant role. Injecting CO_2 into geological formations leverages interactions with these inorganic carbon compounds, resulting in stable carbonate formations that trap CO_2 permanently. This aspect of CCS, known as mineral carbonation, is being explored as a viable method for long-term carbon storage. By enhancing our understanding of mineral weathering and carbonate formation, scientists can better assess the viability of inorganic carbon sequestration as a climate mitigation strategy. For example, promoting silicate weathering through the addition of minerals like basalt to soil is being studied as a means of enhancing carbon capture in agricultural landscapes, providing both sequestration and soil health benefits.

Cotton Cultivation and Carbon Sequestration

In agriculture, cotton cultivation presents unique opportunities for carbon sequestration. Cotton plants naturally absorb about 0.5 kg more carbon than they emit, making them net positive for carbon capture. Cotton farming practices, if managed sustainably, can contribute significantly to soil carbon storage through various mechanisms. Key practices in sustainable cotton cultivation include efficient irrigation, optimized fertiliser use, and incorporation of organic matter to enhance soil health and carbon retention. However, the sustainability and carbon sequestration potential of cotton farming must be understood within broader environmental, social, and economic contexts, including water use, pesticide management, and labour practices.

Several best management practices in cotton farming support carbon sequestration. Techniques such as cover cropping, intercropping, mulching, and applying biochar help build soil organic carbon and improve soil structure (Adhikary *et al.,* 2017). For instance, cover crops and intercropping can reduce soil erosion, maintain moisture, and introduce organic carbon into the soil. At the same time, biochar adds long-lasting carbon and nutrients, enhancing soil fertility and resilience. These practices not only sequester carbon but also improve soil quality, contributing to sustainable land use.

Technological Innovations and Sustainable Practices in Cotton Production

The integration of advanced technologies and regenerative practices has made cotton farming increasingly sustainable. Precision agriculture, which uses data-driven techniques to optimise inputs like water and fertilisers, reduces carbon emissions and minimises resource waste. Regenerative cotton farming emphasises soil regeneration, biodiversity, and holistic farm management, incorporating methods like no-till farming and agroforestry to increase soil carbon and reduce CO_2 emissions.

Certification systems, such as the Better Cotton Initiative (BCI) and organic cotton standards, play a crucial role in promoting sustainable cotton production.

These systems promote eco-friendly practices, including reduced chemical use, water conservation, and enhanced soil health. Certifications emphasise sustainable practices that help cotton producers adopt carbon sequestration measures and align with broader climate goals. These programs ensure that sustainable cotton production not only meets environmental standards but also promotes social and economic benefits for farming communities, thus supporting an inclusive approach to sustainability in the cotton industry.

Therefore, mineral weathering and sustainable cotton farming practices both offer promising avenues for carbon sequestration. By enhancing inorganic carbon through stable carbonate formation and promoting sustainable agricultural practices, these approaches provide scalable solutions for mitigating climate change. Sustainable cotton farming that incorporates carbon-conscious practices, paired with certification standards, supports a shift towards climate-smart agriculture while improving soil health and promoting ecosystem resilience.

Conclusions

Both organic and mineral weathering, as well as sustainable cotton farming practices, offer promising pathways for carbon sequestration, thereby contributing to long-term climate change mitigation. The process of mineral weathering, particularly involving silicate minerals, naturally consumes atmospheric CO_2 , transforming it into stable carbonates that can be stored within soils and geological formations for extended periods. In agricultural settings, sustainable cotton cultivation practices, such as cover cropping, biochar application, and precision agriculture, not only enhance soil carbon but also improve soil health, resilience, and overall productivity.

Cotton, as a carbon-sequestering crop, exhibits a net positive potential by absorbing more carbon than it emits, particularly when sustainable practices are implemented. Additionally, certification programs like the Better Cotton Initiative (BCI) and organic cotton standards promote environmentally friendly and socially responsible practices within the cotton industry. These initiatives help cotton producers integrate carbon-conscious farming techniques, supporting both climate action and economic sustainability for farming communities.

Together, the strategies of mineral weathering and sustainable cotton cultivation represent complementary approaches to reducing atmospheric CO_2. By investing in these natural and agricultural methods, we can work towards a more balanced carbon cycle, improved soil health, and a resilient agricultural ecosystem, aligning with global sustainability goals.

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