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Carbon Sequestration in Agricultural Soil: Technique and their Efficiency

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Developing technologies to slow the rate of increase in the atmospheric concentration of carbon dioxide (CO_2) from annual emissions, such as energy, process industries, land-use change, and soil cultivation, is a major challenge of the twenty-first century. Severe ecological and economic disruptions result from the erratic changes in climate systems caused by the skyrocketing amounts of atmospheric CO_2 and other greenhouse gases (GHGs). Through the process of carbon sequestration, net greenhouse gas emissions can be reduced, hence mitigating climate change. Both biotic and abiotic variables can contribute to the long-term sequestration of carbon, or carbon stabilisation. The compilation of past and present methods for sequestering soil organic carbon is crucial, considering the need of measuring and tracking soil carbon at the point, field, regional, and ecosystem levels. This study attempts to provide an overview of the literature about the function of various agricultural management techniques for sequestering carbon and the ways in which they help to stabilize atmospheric carbon.

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1. INTRODUCTION

Global surface temperatures have increased by 0.88̊C on average since the late 19th century, and 11 of the 12 warmest years ever recorded have occurred since 1995 [1]. The IPCC [2] predicts that in the twenty-first century, the Earth's mean temperature would increase by 1.55 to 5.88 degrees Celsius. The rate of rise in global temperature every decade since 1975 has been 0.158̊C. Aside from the 15–23 cm rise in sea level that has happened throughout the 20th century [1], notable changes in ecosystems and the frequency and intensity of wildfires have also occurred [3,4]. According to Devi et al. [5,6], the reason for these and other known changes in climate is the emission of greenhouse gases (GHGs) as a result of anthropogenic activities such deforestation, soil cultivation, changing land uses, burning biomass, and draining wetlands. Between 1850 and 2005, the concentration of carbon dioxide (CO_2) increased from 280 ppmv to 380 ppmv. At present, the rate of increase is 1.7 ppmv yr^{-1}, or 0.46% yr^{-1} [7,1]. This represents a 31% rise in focus. The contents of methane (CH_4) and nitrous oxide (N_2O) have also been steadily rising during the same time period [2,1,7]. Global climate change has been identified as the most important environmental, economic and social challenge faced by humankind. Greenhouse gases (GHG) in the earth's atmosphere is increasing and causing climate change [8].

Reducing the risks linked to global warming requires stabilizing the atmosphere's concentrations of CO_2 and other greenhouse gases [9,10]. Schrag, [11] states that there are three ways to reduce CO_2 emissions: (i) reducing the amount of energy used worldwide; (ii) developing fuel that has little or no carbon; and (iii) employing both natural and manmade means to absorb CO_2 from point sources or the atmosphere. The type of management techniques applied can influence climate regulation by identifying whether soil is a possible source or sink of atmospheric carbon dioxide (CO_2). Soil has an important role in sequestering carbon depending on its quality and ability to support biomass development [12-14]. In the top 1 m of its surface, soil maintains 1500–2400 pg (peta grammes = 10_{15} g) of organic C, according to Ciais et al. [15]. One of the most feasible and inexpensive ways to mitigate the consequences of climate change is to store soil organic carbon (SOC), which also has the added advantage of improving soil fertility and other ecosystem services [16].

One important mechanism for mitigating the effects of climate change has been thought to be carbon sequestration in agricultural soils [17]. Despite a few basic unanswered problems about carbon persistence and stabilisation [18] and the economic, political, and social elements [19], there is broad consensus about the practical use of carbon-farming [20]. Agriculture occupies one-third of the world's arable land [6]. Developing appropriate soil and land management practices is essential to increase the potential of SOC stocks and employ agricultural soil as a sink of CO_2 [21]. Some optimistic forecasts suggest that agricultural crop root growth might store enough soil carbon in the ground to meet the expected amount of human emissions over the next 20 years [22]. Sommer & Bossio [23], on the other hand, argued that agricultural soil might not absorb carbon at the expected rate and might become saturated after reaching equilibrium. A plethora of evidence suggests that sequestering carbon in agricultural soil is not only possible but also has several benefits for improving soil quality and production, despite differing opinions regarding its full potential [24]. An increase in atmospheric concentration of CO_2 from 280 ppmv in 1750 to 367 ppmv in 1999 is attributed to emissions from fossil fuel combustion estimated at 270±30 Pg C and land use change at 136±55 Pg. Of the emissions from land use change, 78±12 Pg is estimated from depletion of soil organic carbon (SOC) pool. Most agricultural soils have lost 50 to 70% of their original SOC pool, and the depletion is exacerbated by further soil degradation and desertification [25].

2. CARBON SEQUESTRATION

Carbon dioxide is the most common greenhouse gas produced. Carbon sequestration is the process of removing and storing carbon dioxide from the atmosphere. It is crucial to stop climate change by reducing the amount of CO_2 in the atmosphere. The two main methods of sequestering carbon are geologic and biologic sequestration, which is often referred to as biosequestration [26]. Biologic carbon sequestration is one of the processes that naturally take place as part of the carbon cycle. Around 3/4 of the earth's terrestrial carbon is found in the top metre of soil worldwide; yet, there tremendous of opportunity to store more carbon in the soil.

Humans may make it better by using technology and purposeful actions. CO_2 is extracted from the atmosphere naturally by chemical, biological, and physical processes. These processes can be sped up by carbon farming, or changing the way land is utilised for agriculture. One type of artificial process development that has been utilised to get equivalent outcomes is carbon capture and storage. In order to capture and store carbon dioxide produced by underground or oceanic action, technology is used.

On a broad scale, at the landscape and regional level, as well as on a vertical scale in the soil profile, the measuring standards for quick and economical assessments of soil carbon concentration and carbon sequestration are currently being developed. Therefore, it is imperative to identify practical ways to raise SOC stocks while both boosting and preserving high agricultural output. Thus, increasing carbon inputs should be the primary management strategy to improve SOC storage. The addition of straw, extensification through arable-ley rotations, the use of sewage sludge or organic manure as supplements, and, more recently, the use of winter cover crops are all often recommended methods for boosting carbon inputs. Intercrops, also known as catch crops or cover crops, are crops that are planted in lieu of bare fallow throughout the winter and then turned over as green manure prior to the main crop being sown.

3. SOIL ORGANIC CARBON POOLS

The various pools of soil organic carbon differ in terms of their chemical makeup, degree of decomposition, and length of time the carbon stays in the soil—a quantity that is sometimes referred to as "mean residence time." The percentage of various carbon pools in soil can be affected by management [27]. There are three types of organic carbon pools: the recalcitrant or inert fraction that takes hundreds to thousands of years to decompose and is mostly inaccessible to microorganisms, and the active or labile pools that break down relatively quickly and produce a lot of CO_2. Soil management strategies have a significant impact on the labile and resistant pools, as they are dynamic. The labile and resistant pools give rise to the stable organic carbon pools, which are present in aggregates or adsorbed on mineral surfaces. Increasing the resistive and inert C pools is crucial to maximising the durability of additional C in soil [28]. After a year of decomposition, more than two-thirds of the 100 g of organic carbon in a residue will be converted to CO_2, leaving less than one-third in the soil—part of which will stay in the cells of soil organisms, but a greater portion as soil humus [29]. The term 'carbon sequestration' is commonly used to describe any increase in soil organic carbon (SOC) content caused by a change in land management, with the implication that increased soil carbon (C) storage mitigates climate change [30].

Plant residues' initial rate of breakdown has a broad correlation with indexes of their bulk chemical makeup. Compound-specific isotopic analysis, however, showed that certain molecules, such lignin or plant lipids, which are expected to survive in soils, actually break down faster than the majority of the organic matter. Moreover, some substances that may be unstable, like sugars, can endure for decades as opposed to only a few weeks. The complex interactions between organic matter and its environment, such as the interdependence of compound chemistry, reactive mineral surfaces, climate, water availability, acidity, redox state, and the presence of potential degraders in the immediate microenvironment, are primarily responsible for the persistence of soil organic carbon and are not primarily a molecular property [31].

4. TECHNIQUES FOR CARBON SEQUESTRATION IN AGRICULTURAL SOIL

There is presently a dearth of scientific literature evaluating various scenarios for increased storage of carbon. When land usage becomes more sustainable, there is the greatest potential for sequestering carbon. Significant sequestration of CO_2 from the atmospheric pool into one of the other global pools is possible through a number of technological interventions. These fall into one of two major categories: sequestration, biotic and abiotic sequestration [32]. A market for carbon emission reduction would allow farmers to profit financially from the process of lowering agricultural greenhouse gas emissions, of which soil carbon sequestration is one method. Sustainability of the environment is also aided by several management strategies that target soil sinks for the storage of carbon. Increasing the soil's organic matter content enhances its agronomic qualities. More biodiversity results from improved soil and crop production, improved water conservation, less erosion, and improved animal habitat and species protection.

According to Kundu et al. [33], when comparing different land use systems, agro-ecosystems store approximately 17%, forests store approximately 39%, and grasslands store approximately 34% of the global terrestrial stock of carbon. Soil carbon reservoirs were negatively impacted when grassland or forest land systems were converted to agriculture systems [34]. A variety of agricultural management techniques should thus be used to provide enhanced SOC storage, which is necessary to maintain soil productivity and prevent land degradation. Crop management, nutrient management, land use systems, agroforestry, and nanotechnology are among these agricultural management techniques that increase carbon inputs into the soil. Tillage, fallow removal, erosion control, and methane mitigation in wetlands collectively limit carbon loss [35].

Crop management: Cropping strategies like intercropping, cover crops, and crop rotation are essential for achieving the best possible yield from carbon trapped in biomass that stays in the soil, thereby maximising the efficiency of carbon sequestration in agriculture. Chethankumar et al. [36] investigated the effects of several cropping systems, such as rice-rice-*Sesbania bispinosa* and rice-rice-fallow, on soil health and the carbon pool at different depths in a wetland riverine alluvial soil. The findings demonstrated that, in all cropping systems examined, surface soils had larger SOC contents and distinct carbon fractions in comparison to lower depths. Moreover, ecosystems with continuous cropping systems were shown to have higher SOC stocks than those with fallow systems. Increased cropping intensity combined with higher C input results in higher SOC [37]. In unkempt regions, cover crops improve the carbon budget by increasing the amount of carbon input and preventing carbon loss due to erosion. When comparing cover crop management to conventional tillage, the maximum soil organic carbon concentration is observed in slopes and flat regions [38].

Incorporating legume residue into cropping systems improves the rate of carbon sequestration [39,40] because it stabilises the non-labile carbon pool, which leads to the long-term persistence of soil organic carbon. Grain legumes often have strong, deep roots that store carbon in the soil. Additionally, the exudates from the roots serve as sources of carbon. In soil with a lengthy residence duration, the roots of legumes endowed with larger concentrations of lignin-type chemicals contribute to non-labile C [41]. It is advantageous to use Si-rich and deeply rooted crops in carbon sequestration efforts. Rather than coming from shoots and leaf litter, roots are the primary source of carbon in soil. The quantity of carbon that can be sequestered in the steady-state increases with the length of time that a given type of carbon is stored below ground until it is re-respired or released [42,43].

Management of nutrients: The total input of crop residues on the surface or incorporated into the soil greatly influences the SOC concentration in the surface soil (0–15 cm) [44]. Residue integration, as opposed to residue removal or burning, recorded the greatest total carbon across the various agricultural residue management techniques [45]. In a long-term fertiliser experiment, the carbon build-up in soil treated with manure and chemical fertilisers was much higher under organic nutrient management. However, with INM, the percentage of slow carbon to total carbon was greater. Both long-term fertiliser tests and permanent manurial trials showed that the passive pool contributed more to total organic carbon [46]. Two humic acids from compost and lignite, each of which had a different hydrophobic property, were added to an incubation experiment by Spaccini et al. [47]. The results demonstrated that the more hydrophobic the humic material used, the more organic carbon was sequestered in the soil.

Organic fertilizer mostly comprises carbon in its stable form. When compared to other organic sources, rice husk compost significantly improved the soil's organic carbon content, as noted by Rajalekshmi and Bastin [48]. Following soil incorporation, compost was found to be potentially more suitable to reduce CO_2 equivalent emissions and N_2O emissions than leguminous green manure, thereby reducing global warming. Alluvione et al. [49] evaluated the greenhouse gas emission rate from different nitrogen fertiliser applied soils.

Soil tillage operation: By altering agricultural management techniques including tillage, clearing fallows, controlling erosion, and mitigating methane emissions, carbon loss may be decreased. Because it has an impact on both aggravating and degrading processes, soil tillage has an impact on SOC. Humification of crop residue and other biomass, a rise in the resistant or non-labile fraction of SOC, sequestration of SOC through the creation of organo-mineral complexes, an increase in stable aggregation, and deep placement of SOC in sub-soil layers are among the soil aggrading processes that improve SOC. On the other hand, mineralization, leaching, and erosion are soil-degrading activities that negatively affect SOC [27].

Land-use systems: The land-use systems involving rice in the Kazhakuttam series (coastal sandy soils), tea in the Ponmudi series, homestead in the Trivandrum series, coconut in the Amaravila series, rubber in the Nedumangad (laterite soils) and Kallar series (forest soils), vegetables in the Vellayani series (red loam soils), and coconut in the Amaravila series all made a substantial contribution to SOC addition [50]. The relationship between plant species density and soil carbon sequestration was investigated in Thrissur district homesteads by Saha et al. [51]. The findings showed that home gardens with medium and low species densities had comparatively 7 and 14% less soil organic carbon, respectively, and that home gardens with high species density had the highest soil organic carbon per unit area (119.3 Mg ha^{-1}). Dhanya [52] states that, among the several land-use systems, rice and rice-fish supplied a greater passive pool of carbon to the total organic carbon, particularly in the acid sulphate soils of the Kallara series.

Agroforestry: The aboveground and belowground portions of the agroforestry ecosystem are where carbon sequestration takes place. The process of incorporating carbon into plant matter, either in the harvested product or in the portions that stay on the site in a living form, is known as aboveground carbon storage. The potential for this process varies greatly, ranging from 0.29 to 15.21 Mg ha^{-1} yr^{-1}. The capture of atmospheric CO_2 during photosynthesis and the transfer of fixed carbon into plants are the mechanisms behind aboveground carbon sequestration. Roughly two thirds of all carbon sequestration takes place below earth, where it is claimed that carbon is stored in soil organic matter. Forests have the greatest documented soil organic carbon concentration, followed by arable crops, tree plantations, and agroforestry systems. In agroforestry systems, the capacity for soil carbon sequestration varies from 2.72 to 18.9 Mg ha^{-1} yr^{-1} [53]. Agroforestry replaced agriculture, which greatly enhanced SOC stock by 26 and 40% at 0–15 and 0–30 cm, respectively [54].

Elimination of fallow fields: To improve SOC sequestration, a switch from fallow to more intensive cropping systems using no-till is required. Compared to continuous cropping, the crop fallow system was shown to have a substantially larger negative C sequestration rate or C losses, which led to yearly C losses of 62% to 66% [55].

Control of soil erosion: Finer soil particles and related SOC are preferentially transported away from eroding slopes to various low-lying depositional sites as a result of erosion, which causes the detachment of surface soil and exposes SOC that is physically protected within aggregates and clay domains. Because deep soils in agricultural lowlands and sedimentary basins typically have elevated ancient C stocks, burial is thought to preserve SOC against decomposition after detachment and transit. 0.4 to 0.6 Pg C yr^{-1} in erosion-induced deposition and burial may occur annually, as opposed to 0.8 to 1.2 Pg C yr^{-1} released into the atmosphere [56].

Methane mitigation: In 2005, rice fields in India reported a methane emission of 2.92 Tg yr^{-1} [57] Anand. These fields are also responsible for producing 30% of the world's agricultural methane [58]. Methane emissions can be reduced by altering irrigation techniques and controlling organic inputs. In comparison to other organic sources including FYM, green manure, and wheat stubbles, the cumulative quantity of methane released (kg ha-^{1}) from soil can be decreased by integrating rice straw [59]. Rice that is dried intermittently emits less methane [60].

Phytoliths: Phytoliths are tiny, inflexible silica structures that are present in some plant tissues. The organic carbon within the structures is physically shielded by the hard silica shell. There are differences in the rates of phytolith synthesis and the amount of carbon occluded in phytoliths both between and within plant communities [61]. "Phytolith production was recognised to be abundant in agricultural plant species, including barley, maize, rice, sorghum, sugarcane, and wheat. According to Kundu et al. [33], the phytolith C bio-sequestration fluxes from sugarcane, wheat, rice, and millet can reach up to 0.36, 0.13, 0.25, and 0.04 mg-e-CO_2 ha^{-1} $year^{-1}$, respectively.

Nanotechnology: The development of nano-adsorbents with a high specific surface area for the purpose of retaining CO_2 in soil is made possible by nanotechnology. It has been demonstrated that natural nanoparticles, such as oxyhydroxides, hydrous Fe oxides, and nanoclays, have plausible impacts on soil carbon stabilisation. It has been suggested that nanoparticles' distinctive electrical, magnetic, kinetic, and optical characteristics improve soil carbon stabilisation [62].

Biochar: Biochar is a solid material obtained from the carbonization of any biomass including weeds, crop residues and other wastes of plant origin. Biochar plays an important role in climate change mitigation by sequestering carbon in the soil and reducing nitrous oxide (N_2O) and methane (CH_4) gas emissions to the environment through enhancing soil absorption [63]. Corresponding to other organic supplements such as FYM and vermicompost, the application of biochar had a notable impact on lowering CO_2 emissions; moreover, the emission rate remained nearly constant, highlighting the stability of biochar C in soil [64]. By converting biomass C into biochar C, more of the original C is sequestered—roughly 50%—than after burning (3%) and biological decomposition (<10–20% after 5–10 years). This produces more stable soil C than burning or applying biomass directly to the land. Compared to regular biomass, biochar contains twice as much carbon. A little over half of the biomass is pyrolyzed, produced biochar, and then repurposed as soil [65].

5. CARBON STABILIZATION

5.1 Biotic Organic Carbon Stabilization

5.1.1 Soil microbes, plants and arbuscular mycorrhizal fungi

Soil microbes: The primary sources of organic molecules that are stable over an extended period of time are soil microbes. Liquid chemicals that are metabolised by microbes and stabilised as microbial leftovers in organic mineral complexes account for a significant fraction of soil C. Thus, one crucial factor that can control soil organic matter turnover and preserve the equilibrium between soil carbon storage and atmospheric CO_2 release is microbial diversity. The interactions between earthworms, ants, termites, and other ecosystem engineers, as well as the soil mineral matrix, determine the stability of organic matter over the long run [66]. There is an enormous range of creatures, including microbes, macrofauna, microfauna, and megafauna, that are housed in soils, both in terms of size and function. The most well-known category of them are the ecosystem engineers, who work by breaking up trash, blending it into the soil profile through bioturbation, and facilitating the movement of dissolved organic matter. By creating biogenic structures—such as castings, galleries, veneers, fungus wheels, termite or ant hills—they also aid in the stabilisation of carbon. Depending on the makeup of ingested OM, the C in these compounds may be stabilised by organo-mineral interactions. [66].

The earthworm-mediated "C trap" (ECT) disrupts the typical processes of carbon sequestration, and the majority of carbon flows quickly into the earthworm stomach where it is transformed into stabilised forms. Both earthworms and microbiota are probably C-limited in a system with low SOC concentration because more of the C activated by the earthworms is needed to support their metabolism and is soon lost as CO_2 emissions; as a result, C mineralization may be the predominant process, with less C stabilised. On the other hand, in a system with a high SOC concentration, the C that is metabolised by bacteria and earthworms may represent a minor fraction of a significant pool of C that can be mineralized. As a result, earthworms' very little stimulating influence on CO_2 generation is diminished, and C stabilisation could be the main mechanism [67].

Plants: The primary sources of soil organic C are symbiotic (nitrogen-fixing and mycorrhizal) relationships, litter formation (shoots and roots), and root exudates. By generating poorly degradable chemicals, encouraging stable aggregate formation, and reducing erosion, plants aid in the stabilisation mechanisms that preserve soil organic carbon [67,68].

Arbuscular Mycorrhizal Fungi (AMF): Mycorrhizal hyphae stabilise and preserve the organic matter in soil aggregates; their exudates can raise soil carbon inputs, which can occasionally surpass those of leaf litter and fine root turnover. Because these exudates effectively compete with saprophytic bacteria and fungi, the pace at which organic matter decomposes is slowed down. Furthermore, by incorporating carbon molecules into extremely stable compounds like mineral-associated SOM fractions, which also have the longest mean residence durations in soil, AM fungi might decrease the availability of carbon compounds in the rhizosphere [69]. Arbuscular mycorrhizal fungus create a large amount of glomalin, a glycoprotein with 30–40% carbon, on their hyphae and spores in the soil and around their roots. It enters the soil and binds organic matter to silt, sand, and clay particles to create clumps. It also stabilises the soil, helps with tilth, or soil structure, and prevents other stored carbon from escaping [70].

5.1.2 Abiotic organic carbon stabilization

Biochemical recalcitrance: The presence of aromatic polymers and other chemically complex compounds in SOM that are hard for microorganisms to break down leads to biochemical recalcitrance. Lignocellin, a primary constituent of woody plants, is a typical example. Though it must cooperate with other elements like physical protection and organo-mineral stabilisation to stabilise SOC, current research indicates that this component alone does not cause long-term soil C recalcitrance [70].

Macro and micro soil aggregates: It is the technique of binding organic carbon in soil aggregates to shield it from microbial populations and stop it from degrading. Aggregates maintain soil organic carbon by influencing microbial turnover, regulating food web interactions, and forming a physical barrier between microorganisms, microbial enzymes, and their substrates [71]. The methods by which soil aggregates stabilise soil carbon were shown by Nair et al. [70]. Large macroaggregates made up of a mix of recently added SOM that is physically shielded within the macroaggregate but will break down quickly if exposed stabilise soil aggregates. Over time, refractory organic mineral complexes are created from this fresh OM by a combination of abiotic processes and microbial activity, provided that the macroaggregate stays intact. As a result, the concentration of resistant microaggregates within macroaggregates gradually rises, increasing the quantity of carbon stored in the soil.

The coarse intra-aggregate particulate organic matter (iPOM) holds macroaggregates together. Microbes break down the iPOM by releasing polysaccharides and other compounds into the soil that serve as binding agents. These binding agents give the macroaggregate structural stability by holding the mineral particles and microaggregates together. Additionally, by decreasing the flow of air and water within the macroaggregate, anoxic conditions are created, which in turn slows down microbial activity and the breakdown of SOM. In addition to the hyphae and roots that surround the iPOM, the macroaggregate is further stabilised and protected physically by hyphal exudates from arbuscular mycorrhizal fungi like glomalin. Therefore, the creation of microaggregates (less than 250 mm), which contain the oldest and most resistant SOC, throughout the carbon stabilisation process depends on the stability and production of macroaggregates as well as the availability of new SOM [67].

Organic binding agents: The formation and stabilisation of aggregates are facilitated by three main organic-binding agents: transitory, temporary, and permanent [72]. Transient organic binding agents: These agents are mostly constituted of glucose-like components, such as mono- and polysaccharides, and are quickly broken down by microbes. They are effective for a few weeks, after which their impact starts to wane. After polysaccharides deprotonate, their functional group acquires a negative charge and interacts with positively charged oxides to form stable organic-inorganic microstructures. Temporary organic binding agents: Binding agents can last for several months or even years. They are made up of roots and hyphae. Persistent organic binding agents: These agents are made of amorphous forms of Fe, Al, and Al-silicates combined with degraded humic components [72].

Chemical stabilization- organo-mineral complexes: The process of converting and binding organic carbon with minerals to create organomineral complexes that can withstand long periods of time in the soil is known as organomineral stabilisation. According to Dignac et al. 2017 [66], soil minerals like clay minerals (phyllosilicates), as well as various metallic oxyhydroxide forms and poorly crystallised aluminosilicates (allophane or imogolite types), can shield soil organic matter from the mineralizing activity of microorganisms. These finely split minerals physically shield organic matter (OM) from soil microbes that degrade it by adsorption or by trapping OM inside sub-micron aggregates. Different forms of interactions, such as anionic ligand exchange, cationic ligand exchange, cationic bridges, or so-called weak contacts, cause OM adsorption by soil minerals. Complex soil organic compounds are formed by poorly crystallised minerals into organomineral nano-complexes, which range in size from a few nanometers to a few hundred nanometers and have significant concentrations of C. Before reaching their ultimate crystalline development stages (imogolite and/or allophane), partly crystallised phases known as protoimogolites—produced by the weathering of fundamental mineral phases—complex the OM. Organic molecules are stabilised by these proto-imogolites over thousands of years. Amorphous minerals with nanoscale size are produced when minerals weather or undergo other changes. Their interactions with organic molecules are facilitated by their high reactivity and specific surface area.

5.1.3 Mechanisms of carbon stabilisation under various management approaches

Conservation tillage: Transforming natural vegetation into conventional tillage weakens the formation of new aggregates, disperses clay particles and silt + clay microaggregates, and disturbs soil aggregates." However, in the presence of organic residues and microbial polysaccharides during conservation tillage, microaggregates combine to produce macroaggregates. Through compartmentalization, these stable macroaggregates physically shield a significant amount of organic matter from microbial destruction within them, rendering them unavailable to bacteria for breakdown. When comparing conservation tillage to conventional tillage, the quantity of C-rich macro-aggregates rose while the amount of C-depleted micro-aggregates dropped [73].

Deep-rooted crops: Deep rooted crops have a mean residence duration in soils that is 2.4 times longer for C produced from roots than from shoots. The reasons behind the stabilisation of root-derived SOM compared to shoot-derived carbon are as follows: the root tissues' chemical resistance; exudation's contribution of carbon compounds into the rhizosphere; physico-chemical protection in deeper horizons; micrometer-scale physical protection via root-hair and mycorrhiza activities; and chemical interactions with metal ions [74]. Through a variety of mechanisms, including increased production of root exudates that act as a glue between soil particles, soil particle trapping made possible by the entanglement of roots and hyphae, increased frequency of wetting-drying cycles in the soil in relation to water acquisition by roots, input of plant residues that contribute to macroaggregate stability, and stimulation of the production of microbial metabolites involved in microaggregate stability, plant roots contribute to the formation of stable aggregates and improve aggregate stability [75].

Compost: Compared to inorganic fertilisers, the application of compost with high phenolic and lignin residues has been shown to increase the buildup of lignocelluloses and hemicelluloses, resulting in a reduction in the mineralization rate per unit of SOC. According to the results of the long-term experiment carried out by Favoino and Hogg [76], using compost manure continuously produced twice as much SOC content as chemical fertilisers and implied that a specific percentage of the easily obtainable organic carbon in compost that was mineralized was changed into stable organic matter. While some carbon does mineralize from this stable organic matter, it does so far more slowly than it does from resistive organic matter.

Clay humic complexes: Polyvalent cations have the ability to adsorb the organic molecules of compost to the clay minerals. Clay particles absorb organic anions of C-rich humic colloids and polysaccharides via polyvalent metals. These complexes are shielded from microbial breakdown by occurring inside clay domains that create clusters of micro aggregates. The valency of the metals bridging the inorganic and organic anions in the following sequence (Al^{+3} > Fe^{+3} > Ca^{+2} > Na^{+}) that determines the strength of the bonds. Following the addition and breakdown of compost, bonding processes such H-bonding, van der Waal's forces, and Coulombic attractions regulate the formation of clay-humic complexes. Three crucial physical and biochemical processes are carried out by these organo-mineral complexes to stabilise C: (i) organic materials react through adsorption with clay particles; (ii) clay surfaces polymerize humic substances; and (iii) the polymerized organic compounds are chemically and physically sequestered by clay crystals, rendering them inaccessible to soil organisms [77]. The surface area, ionic charge, kind, and chemical and geochemical makeup of clay minerals all affect how quickly C stabilises. Compared to clay minerals dominated by kaolinite and chlorite, smectite-dominated clay preferred a higher SOC storage [77].

Nanoparticles: The organic carbon content in each aggregate size fraction and the mean weight diameter of water-stable soil aggregates are efficiently increased by nano-zeolite, nano-ZnO, and nano-Fe particles. Clay crystals and organic molecules are shielded from breakdown by cation bridges formed by the high calcium concentration of zeolite minerals. It has been documented that nano-ZnO and Fe cause microorganisms to secrete extracellular polysaccharides, which forms stabilised carbon. Additionally, enhancing carbon stabilisation are the electrical, magnetic, kinetic, and optical characteristics of nanoparticles. The development of nano-adsorbents with a high specific surface area and high CO2 retention is facilitated by nanotechnology. CO_2 may be removed using carbon nanotubes and nanotubes functionalized with amines by physical adsorption techniques. Because of activated carbon, both single- and multiwalled carbon nanotubes have a high capacity for CO_2 adsorption. Another article mentioned CaO as a possible CO_2 absorber, which is generated from nano-sized $CaCO_3$. As a result, soil may contain natural nanoparticles with the ability to stabilise SOC over an extended period of time [62].

6. CROPS FOR CARBON FARMING

A commitment to agricultural techniques that support soil carbon sequestration is required for carbon farming to produce revenue-producing carbon credits. The goal of carbon farming practices like cover crops is to increase soils' ability to store carbon in places where it can be retained for a long period [78]. Incentives are given to farmers since increasing the soil carbon budget and changing agricultural practices to be more climate-friendly are necessary for soil carbon sequestration. In addition to supporting agricultural yield through enhanced soil health, an improved soil carbon budget creates a pool from which carbon may be transformed into recalcitrant forms for long-term storage as a global warming mitigation strategy. According to this viewpoint, researchers suggest designing crop ideotypes that are highly productive for fuel, food, and feed while also having the capacity to encourage greater soil carbon contributions and enhance the subsurface ecosystem. Over time, these carbon farming techniques can lower expenses, improve the quality of the output, and open up new sources of income for farmers [17].

The goal of carbon farming is to increase the rate at which CO_2 is taken up from the atmosphere and transformed into plant matter and organic matter for the soil. This goal will have two beneficial effects: it will enhance soil health, which will raise agricultural yield, and it will increase the possibility of long-term carbon storage, which will reduce greenhouse gas emissions. Jansson et al. [78] contend that the following characteristics should be present in crops intended for carbon farming: (1) greater allocation of carbon below ground for larger and deeper root biomass; (2) interactions with a customised, synthetic soil microbiome for increased rhizosphere sink strength and enhanced PGP properties that facilitate nutrient acquisition and water-use efficiency; and (3) increased source strength for improved photosynthesis and biomass accumulation. In the upcoming decades, carbon farming presents a chance to take use of the significant potential that comes with fusing agriculture with the rhizosphere bacteria to encourage soil carbon storage [71]. Therefore, planning crops for carbon farming is in line with the consensus reached in the Paris Climate Agreement, which states that finding economically effective ways to control global warming goes beyond only reducing emissions [79].

Storing carbon in the soil is a major goal of carbon farming. The following methods are beneficial for sequestering carbon in soil and are frequently suggested by agronomists.

Reduced use of fertiliser: Chemical inputs can be harmful when used excessively and decrease soils' ability to store carbon. In addition to driving up costs, producing inorganic fertilisers produces a significant amount of greenhouse gas emissions. One strategy to optimise crop nutrient application and enhance soil health at a lower cost is to reduce the use of chemical fertilisers.

Minimised tillage: The rate at which carbon dioxide is emitted from the soil is accelerated by heavy and frequent tilling. Additionally, it disrupts the structure of the soil, which increases the risk of erosion and less productive croplands. Regenerative tillage, which involves little to no ploughing at all, maintains soil carbon and quality, which increases crop output.

Enhanced management of crop residues: Leaving crop leftovers on the fields is another farming tactic for safeguarding the soil. By adding mulch or crop residues like straws to the soil, may improve its fertility and moisture content while also fostering a healthy soil composition by allowing the organic matter to interact with microorganisms.

Eliminating bare fallows: When farmed land is left fallow for a season or longer, the soil is left vulnerable to heat, wind, rain, and weeds, creating an environment where soil carbon may more easily escape. Alternatively, planting crops that fix nitrogen, such as clover, can help retain carbon in the soil and increase the amount of nitrogen in the soil for the following crop.

Enhancing production of cover crops: Introducing cover crops is one of the most advised techniques for carbon farming. These crops are grown differently from the main crop that is typically produced on the farm, with the specific goal of protecting the soil. In addition to lowering surface disturbance, cover crops aid in nutrient uptake, increasing soil organic carbon and fertility.

Planting companion plants: Growing two or more crops simultaneously not only benefits the crops but also the soil, but companion planting improves plant variety. Understanding complimentary crops is essential to maximising crop development and yield. To shield the main crop from insects and pests, for instance, a second crop is seeded.

The majority of farms plan and determine their carbon farming practices before committing to any operational changes. It comes down to knowing the farmer's objectives and the initial field circumstances. Furthermore, data tracking is necessary for accurate accounting of effectively sequestered carbon in carbon farming. Ensuring the production of high-quality carbon credits in agriculture requires rigorous measurement, reporting, and verification (MRV), which includes capturing critical agricultural data. Furthermore, some carbon programmes could just recommend a predetermined range of farming methods without taking into account the unique requirements of a farm. To check if a farm is on track to achieve desired results, best practices in carbon programmes need a regular evaluation of the carbon farming techniques used on the farm.

7. CONCLUSION

Global warming is mostly caused by an increase in CO_2 emissions. Reducing the amount of CO_2 released into the atmosphere will help to mitigate the rise in air temperature that causes global warming. Carbon sequestration efforts can help achieve this. Sequestering carbon (C) and reducing greenhouse gas emissions are two possible uses for soil, particularly in well-manicured agricultural soils. Managed ecosystems (such as forests, soils, and wetlands) can enhance their sink capacity by switching to a prudent land use. Deliberate alteration of biological processes can accelerate CO_2 sequestration through the use of regulatory measures and the establishment of policy incentives. Nonetheless, the effectiveness of these management methods depends on an integrated systems approach. Thus, managing soil organic carbon is essential to achieving excellent soil quality and agricultural sustainability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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