Carbon Sequestration and Stabilisation Mechanisms in the Agricultural Soils: A Review

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Authors' contributions

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

Review Article

ABSTRACT

Rapidly increasing levels of atmospheric CO_2 and other greenhouse gases (GHGs) initiate unprecedented changes in climate systems, leading to severe ecological and economic disruptions. Climate change mitigation is possible through a reduction in net GHG emission by the process of carbon sequestration. Storage of carbon in a stable solid form through direct and indirect fixation in soil leading to carbon sequestration can result in an annual growth rate of 0.4% in the soil carbon stock and significantly reduce CO_2 concentration in the atmosphere. The long term sequestration of carbon, viz, carbon stabilization is possible through both abiotic and biotic factors. This research paper aims to establish a literature review about the role of different agricultural management strategies for carbon sequestration and their stabilization mechanisms. Agricultural practices such as tillage, fallow elimination, erosion control and methane mitigation reduce carbon loss while crop

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management, nutrient management, land use systems, agro forestry and nano technology enhances carbon inputs. These agricultural management practices can facilitate carbon stabilization by acting through both biotic and abiotic mechanisms.

Keywords: Carbon sequestration; carbon pools; carbon stabilization mechanisms; agricultural management strategies.

1. INTRODUCTION

Continuous increase in the concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs) since the industrial revolution in the atmosphere is believed to be responsible for climatic changes and related consequences being experienced across the globe. Even the modern agricultural practices have contributed to the phenomenon. The concentration of CO_2 recorded on October 30, 2019 was 409.17 ppm and that of Oct. 30, 2020 as 411.65 ppm, showing a one-year change of 2.48 ppm. According to the Intergovernmental Panel on Climate Change (IPCC), among all the greenhouse gases, the percentage contribution of CO_2 to global warming is 76%, methane 10%, nitrous oxide 6% and other gases contribute to 2%. Contribution of India to global greenhouse gas emission is 7% of which contribution from agriculture is 14% [1].

"In this context, Kyoto protocol was developed in 1997 in Kyoto, Japan and entered into force on 16 February 2005 with the objectives to stabilize and reduce GHG emissions, mitigate climate change, and promote sustainable development. Even though the protocol primarily addresses the importance of controlling and reducing GHG emissions, i.e., source management, it also recognises the better management of carbon reservoirs and enhancement of carbon sinks in forestry and agriculture through carbon sequestration" [2]. The international 4 per 1000 initiative, launched by France in 2015 ahead of COP21 in Paris also aims to bring together governmental and non-governmental stakeholders devoted to improving soil C stock management.

2. CARBON SEQUESTRATION

"Carbon sequestration is the process of capture and long-term storage of atmospheric carbon dioxide. It is the long-term storage of carbon in the terrestrial biosphere, underground, or the oceans as long-lived carbon pools or resorces so that the build-up of carbon dioxide concentration in the atmosphere will be reduced or slowed

down" [3]. "Simply, carbon sequestration is the process of removing carbon (C) from the atmosphere and depositing it in 'carbon pools' to mitigate the adverse effect of climate change" [4].

Global carbon pool refers to a system or mechanism which can accumulate or release carbon. It can be natural or human-induced. There are five global C pools [5].

3. CARBON SEQUESTRATION- TYPES

The natural process by which terrestrial carbon sequestration occurs is through photosynthesis. However, this is inadequate to cope up with the present-day carbon emission. Therefore, **s**everal technological interventions can be made for significant sequestration of CO_2 from the atmospheric pool into one of the other global pools. These can be grouped into two broad categories: abiotic and biotic sequestration [5].

The abiotic techniques involve the injection of CO_2 into deep oceans, geological strata, old coal mines, oil wells and mineral carbonation. The biotic component on the other hand involves managing higher plants and micro-organisms to remove more CO_2 from the atmosphere and fixing this C in stable terrestrial pools.

"The amount of carbon emitted annually into the atmosphere from natural vegetation, industries, vehicles etc. is estimated at 8.7 Pg C while only 3.8 Pg C yr^{-1} is found in the atmosphere at a given time. This leaves an unaccounted balance of 4.9 Pg C yr^{-1} that is believed to have been sequestered on terrestrial systems (oceans, forests, soils, etc.) which are referred to as the 'missing sink'. The soil is reputed to contain the largest terrestrial carbon pool estimated at approximately 2344 Pg of organic carbon in the first 3 m, 1500 Pg in the first 1 m and 615 Pg stored in the top 20 cm of the soil profile" [6].

3.1 Soil Carbon Sequestration

"Worldwide, SOC in the top 1 meter of soil comprises about 3/4 of the earth's terrestrial carbon; nevertheless, there is tremendous

potential to sequester additional carbon in the soil. According to the Soil Science Society of America, soil carbon sequestration is the storage of carbon in a stable solid form in the soil as a result of direct and indirect fixation of atmospheric CO_2" [7]. "It is the process of transferring carbon dioxide from the atmosphere into the soil of a land unit through plants, plant residues, and other organic solids, which are stored or retained in the unit as part of the soil organic matter" [8].

"The direct fixation of CO_2 involves the natural conversion of CO_2 into soil inorganic compounds such as calcium and magnesium carbonates (938 Pg) while the indirect sequestration takes place when plants produce biomass through the process of photosynthesis (1576 Pg). This biomass is eventually transferred into the soil and indirectly sequestered as soil organic carbon during and after the decomposition process" [5].

3.2 Pools of Soil Organic Carbon

Soil organic carbon is made up of a number of different pools that vary in their chemical composition and stage of decomposition, or based on how long the carbon remains in the soil, a figure often referred to as "mean residence time". Management can influence the proportion of different carbon pools present in soil [9].

"The different pools are *active or labile* which decomposes relatively quickly thereby generating a great deal of CO_2, and *resistant pools* with residence time of 20-40 years and the *recalcitrant or inert* fraction of organic carbon which takes centuries to thousands of years to decompose, and largely unavailable to microorganisms. The labile and resistant pools are active and highly influenced by soil management practices. The stable organic carbon pools originate from labile and resistant pools and is found in aggregates or adsorbed on mineral surfaces. In order to maximize the sustainability of added C in soil, it is essential to increase the resistant and inert C pools" [9]. When 100 g organic carbon in a residue is incorporated into the soil, after one year of decomposition, more than two-thirds of the carbon will be oxidized to CO_2, and less than one-third remains in the soil- some in the cells of soil organisms, but a larger component as soil humus [10].

"The initial decomposition rate of plant residues correlates broadly with indices of their bulk chemical composition. However, compound-specific isotopic analysis revealed that molecules predicted to persist in soils such as lignin or plant lipids have been shown to decompose more rapidly than the bulk of the organic matter. Furthermore, other potentially labile compounds such as sugars can persist not for weeks but for decades. The persistence of soil organic carbon is primarily not a molecular property and which is largely due to complex interactions between organic matter and its environment, such as the interdependence of compound chemistry, reactive mineral surfaces, climate, water availability, soil acidity, soil redox state and the presence of potential degraders in the immediate microenvironment" [11].

3.3 Soil Organic Carbon Stabilization Mechanisms

Soil C stabilization is the decrease in the potential loss of organic carbon by microbial respiration, erosion or leaching [12]. "There are two main types of mechanisms influencing the stabilisation of soil organic C, biotic mechanisms related to living soil biomass and soil biodiversity and abiotic mechanisms like localisation in the soil physical structure and organo mineral interactions" [13].

3.4 Biotic Organic Carbon Stabilization

3.4.1 Plants, AMF and soil microorganisms

Plants- The main source of soil organic C is through litter production (shoots and roots), root exudates and via symbiotic (nitrogen-fixing and mycorrhizal) associations. Plants contribute to soil organic carbon stabilisation mechanisms by producing poorly degradable compounds, by promoting stable aggregate formation and by limiting erosion thus contributing to soil organic carbon conservation [13,14].

AMF- "The organic matter in soil aggregates is stabilized and protected by mycorrhizal hyphae, the exudates of which can increase the carbon inputs into the soil, which sometimes exceed the input of leaf litter and fine root turnover. These exudates are efficient competitors for saprophytic bacteria and fungi, thus reducing the organic matter decomposition rate. In addition to this, AM fungi can reduce the availability of carbon compounds in the rhizosphere by integrating them into very stable compounds such as mineral-associated SOM fractions which also have longest mean residence times in soil" [15].

Glomalin, a glycoprotein containing 30-40% carbon, is produced abundantly on hyphae and spores of arbuscular mycorrhizal fungi in soil and near roots. It permeates organic matter, binding it to silt, sand and clay particles and forms clumps, stabilizes the soil, aids soil structure, or tilth, and keeps other stored carbon from escaping [16].

Soil microorganisms- "These are the main sources of organic compounds stabilised in the long term. A substantial proportion of soil C originates from labile compounds metabolised by microorganisms and stabilised as microbial residues in organomineral complexes. Therefore, microbial diversity is an important parameter that can modulate soil OM turnover, and thus maintain the balance between soil C storage and atmospheric CO_2 emission. Long-term OM stabilisation is controlled by interactions between microorganisms (fungi and bacteria), ecosystem engineers (earthworms, ants and termites) and the soil mineral matrix" [13].

"The diversity of organisms hosted in soils is huge in terms of size and function, encompassing megafauna, macrofauna, microfauna and microorganisms. Among them, the best-known group includes ecosystem engineers which act by fragmenting litter, incorporating it into the soil profile by mixing soil by bioturbation and aiding dissolved OM transport. They also promote C stabilisation by forming biogenic structures (biostructures such as castings, galleries, veneers, fungi wheels, termite or ant hills). The C in these structures can be stabilised through organomineral associations, depending on the composition of ingested OM" [13] (Fig. 1).

Earthworm – "The regular processes of C sequestration are interrupted through earthworm-mediated 'C trap' (ECT), and most of the C flows rapidly into the earthworm gut where it is converted into stabilized forms. In a system with low SOC content, both earthworms and microbiota are likely C-limited, with a greater proportion of the earthworm-activated C used to sustain their metabolism, which is quickly lost as CO_2 emissions; therefore, C mineralization may be the dominant process, with less C stabilized. In contrast, in a system with high SOC content, the C that is metabolized by earthworms and microbiota may account for a small proportion of a large pool of mineralizable C. Thus, the stimulating effect of earthworms on CO_2 emission is reduced in a relative sense, and C stabilization may be the dominant process" [17].

3.5 Abiotic Organic Carbon Stabilization

"Soil organic matter is protected in the soil abiotically by three main processes: biochemical recalcitrance, physical protection and chemical stabilization" [18].

3.5.1 Biochemical recalcitrance

"Biochemical recalcitrance occurs when the chemical makeup of SOM involves aromatic polymers and other structures that are difficult for microbes to break down. A common example is lignin, one of the main components of woody plants. However, recent studies suggest that this factor alone does not lead to long-term soil C recalcitrance but must work in conjunction with other factors such as physical protection and organomineral stabilization to stabilize SOC" [16].
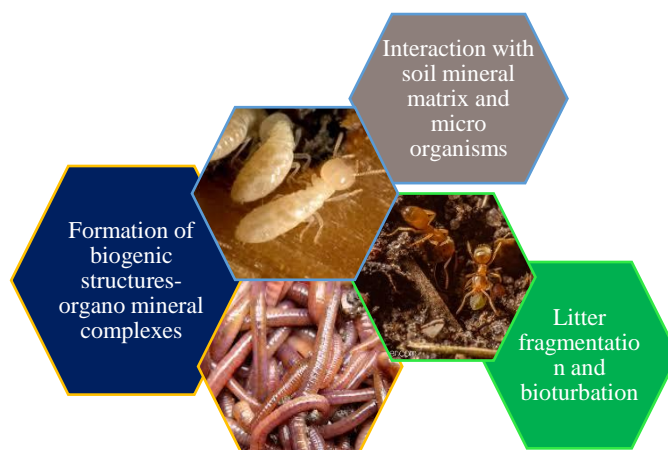

Fig. 1. Ecosystem engineers [13]

3.5.2 Physical protection- macro and micro aggregates

It is the binding of organic carbon in soil aggregates, porotecting it from microbial populations and preventing its degradation.

"Aggregates protect soil organic carbon by (i) forming a physical barrier between microorganisms, microbial enzymes, and their substrates; (ii) controlling food web interactions; and (iii) influencing microbial turnover" [19].

According to Totsche et al. [20], "aggregates are secondary particles formed through the combination of mineral particles with organic and inorganic substances. They range in size from microns to millimeters and are often classified according to their ability to resist slaking in water. Depending on their diameter, they are classified into various size classes. The smallest size fractions among the micro aggregates are composed of recalcitrant organomineral complexes. These are bound together to form larger microaggregates, held together by polysaccharides and humic materials which are also fairly persistent due to biochemical recalcitrance and physical protection. These materials are further bound together as macroaggregates by roots, hyphae, and organic materials that readily decompose but are physically protected within the aggregate. The age and amount of C in each size class also follows this aggregate hierarchy; the highest concentration of C is in the macroaggregates. This C is also, on an average, the youngest. The lowest concentrations of C and the oldest C are in the smallest fraction or microaggregates".

Nair et al. [16] depicted "the mechanisms of soil carbon stabilization by soil aggregates. Soil aggregates are stabilized when large macroaggregates form from a combination of older microaggregates and fresh SOM which is physically protected within the macroaggregate, but readily decompose if exposed. If the macroaggregate remains intact, over time, this fresh OM is converted through a combination of microbial activity and abiotic factors to recalcitrant organomineral complexes. This eventually leads to an increase in the concentration of recalcitrant micro aggregates within macroaggregates, increasing the amount of C sequestered in the soil".

"Macroaggregates are held together by the coarse intra-aggregate particulate organic matter (iPOM). In the process of breaking down of the iPOM, microbes deposit polysaccharides and other chemicals that act as binding agents in the soil. These binding agents stick the mineral particles and micro aggregates together, giving structural integrity to the macroaggregate. This also reduces air and water movement, creating anoxic conditions and slowing down microbial activity and decomposition of SOM within the macroaggregate. Besides, roots and hyphae grow around the iPOM, hyphal exudates from arbuscular mycorrhizal fungi such as glomalin further physically protect and stabilize the macroaggregate. Thus, in the process of carbon stabilization, the formation of microaggregates (<250 mm) where the oldest most recalcitrant SOC is found, hinges on the formation and stability of macroaggregates and the availability of fresh SOM" [17].

3.5.3 Organic binding agents

Three principal organic-binding agents are involved in aggregate formation and stabilization: transient, temporary and persistent [21].

- Transient organic binding agents – These binding agents are rapidly decomposed by microorganisms being composed mostly of glucose-like components (mono- and polysaccharides), lasting effectively only for a period of a few weeks, after which their effect diminishes. The functional group in polysaccharides, upon deprotonation, becomes negatively charged and interact with positively charged oxides, producing stable organic-inorganic microstructures.
- Temporary organic binding agents - Binding agents consist of roots and hyphae and may persist for months and years.
- Persistent organic binding agents - Binding agents are composed of degraded humic materials mixed with amorphous forms of Fe, Al and Al-silicates [21].

3.5.4 Chemical stabilization- organo-mineral complexes

Organomineral stabilization is the conversion and binding of organic carbon with minerals to form organomineral complexes that can remain in the soil for extended periods of time.

Dignac et al. [13] revealed that "soil organic matter can be protected from the mineralising activity of microorganisms by soil minerals such as clay minerals (phyllosilicates), as well as different forms of metallic oxyhydroxides and poorly crystallised aluminosilicates (allophane or imogolite types). These finely divided minerals protect OM by adsorption or by trapping OM within sub-micron aggregates, thus physically protecting it from the degrading action of soil microorganisms. OM adsorption by soil minerals occur through different types of interactions like anionic ligand exchange, cationic ligand exchange, cationic bridges or so-called weak interactions (Fig. 2). Poorly crystallised mineral forms complex soil organic compounds to form organomineral nano-complexes, a few nanometres to a few hundreds of nanometres in size, which contain high C concentrations. The weathering of primary mineral phases produces partially crystallized phases (protoimogolites), which complex the OM before reaching their final crystalline growth stages (imogolite and/or allophane). These proto-imogolites stabilize organic compounds over periods of up to several thousands of years. Weathering or alteration of minerals generates nanometer sized amorphous minerals. Their high reactivity and specific surface area promote their interactions with organic compounds".

3.6 Soil Factors Regulating Soil Organic Carbon Sequestration and Stabilization

3.6.1 Soil texture

Sandy soils, which tend to be well aerated and have the little adsorptive capacity, generally retain little organic carbon. According to Yost and Hartemink [22] "among the different soil orders, sandy soil recorded the highest SOC in spodosols and lowest in aridisols (Fig. 3). Although these sandy soils have a wide range of SOC concentrations, 90% of sandy soils contain less than 30 g SOC kg^{-1} in the topsoils". "Clayey soils, on the other hand, form strong physicochemical bonds between the active surfaces of the clay particles and the organic macromolecules of humus, which thus become resistant to further decay. As the clay content increases in the soil, they combine with SOC to form tight water-resistant stable aggregates, the interiors of which restrict aeration and further resist the decay of occluded organic matter. Clay also helps to protect SOC from breakdown by binding strongly and creating a physical barrier to protect from microbial access. In most cases, clay soils under the same soil conditions and under the same land uses tend to retain more C than sandy soil" [21].

- *Soil moisture*
  "Moisture regimes possess a strong influence on the temperature sensitivity of decomposition of both labile and recalcitrant organic C pools. Within the optimum moisture regime, rate of decomposition of labile and recalcitrant organic C pools is enhanced with an increase in temperature. However, under submerged and dry moisture regimes, the rate of decomposition of both labile and recalcitrant organic C pools is declined, for all temperatures" [23]. Larger concentrations of dissolved organic carbon, microbial biomass carbon, and total organic carbon are noticed under waterlogged soils than drained soils, and greater CO_2 efflux under drained condition than under flooded condition due to enhanced microbial activity and high decomposition rate of soil organic matter [24].

- *Soil temperature*
  "The rate of decomposition of organic carbon doubles for every 8 °C or 9 °C increase in mean annual temperature. The biochemically complex and less labile substrates that normally resist decomposition are more sensitive to high temperature" [25]. Thus an increase in temperature due to global warming can have the momentous capability to hasten the decomposition of the well-preserved ROC pool in soil ecosystems.

- *Soil pH and ESP*
  In general, at 0–15 cm soil depth, organic C decreased with an increase in soil pH and exchangeable sodium percentage (ESP). Enhanced SOC solubility at higher pH is attributed to the decreased occupation of binding sites with protons [26]. The effect of liming on acid soils for 34 years was studied by Aye et al. [27] and concluded that liming decreased total SOC content and large macro-aggregates by up to 30% due to increased microbial activity and reduced physical protection due to continuous cultivation.

- *Soil types*
  "Vertisols and associated soils contain greater C stocks, followed by inceptisols, alfisols and aridisols" [28]. "Vertisols with

smectite as the dominant mineral had larger organic C stocks than illitic inceptisols and kaolinitic alfisols. The passive pools of soil organic carbon also varied with soil types, and among the different Kerala soils, Kaipad and Ponnani Kole soils recorded the highest passive fraction" [29]. The percentage increase in soil organic carbon content under various agricultural management practices also varied with soil types and the SOC concentrations tend to change faster in sandy soils than in finer textured soils (Table 1). The long-term fertilizer trails conducted in different soils across India revealed that the combined application of NPK and FYM resulted in higher soil organic carbon than NPK alone in all the soil types [30]. Similarly, on the addition of FYM and biochar, the amount of CO_2 lost varied with soil types. Biochar addition results in 88% decrease in CO_2 emission in sandy soils while it was only 15% in black soil [31,32].
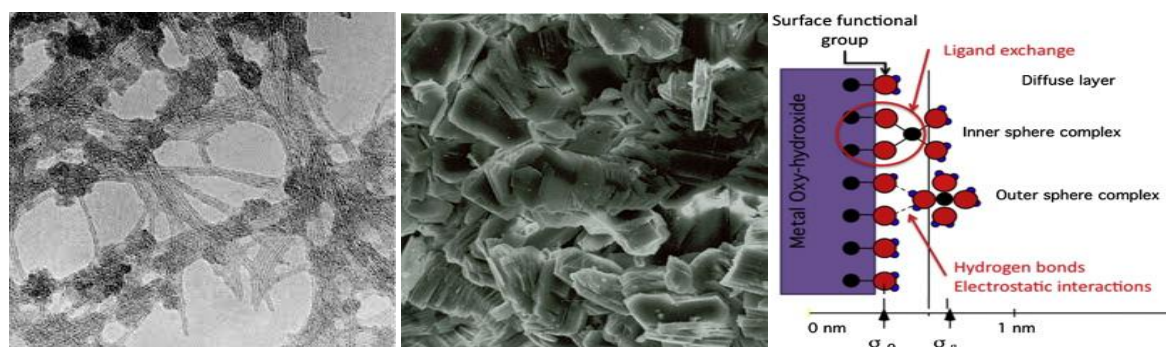

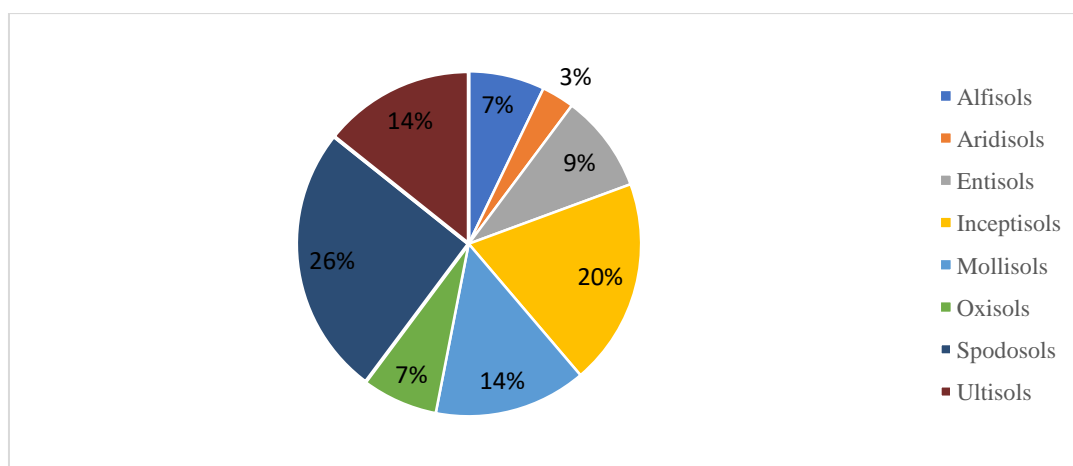**Fig. 2. Clay minerals and dominant bonding mechanisms [13]**

Fig. 3. SOC (g kg^{-1}) of sandy soils by soil order [21]

Table 1. Effect of soil types on carbon sequestration under INM

Soil type	Soil order	% increase in SOC compared to control	Reference
Alluvial soils	Entisols	41.66	[33]
Sandy soils	Inceptisols	83.33	[34]
	Ultisols	46.66	[35]
	Entisols	75.00	[36]
Sandy loam soils	Entisols	58.07	[37]
Loamy soils	Mollisols	18.02	[38]
Laterite soils	Alfisols	43.18	[39]

- ***Clay minerals and Iron oxide coating***
  Saidy et al. [40] reported that the stability of sorbed OC in clay minerals decreased in the order kaolinite>illite>smectite. However, iron oxide coating in kaolinite and smectite also increased the stability of sorbed OM against microbial decomposition. The rate of mineralization of sorbed OC depends upon the bonding mechanisms.

- ***Metal ions***
  Fe oxides have greater potential for carbon storage due to its high surface area and reactivity. Calcium enhances the sorbed OC concentration by approximately 10% to 15% and the concentration will depend upon the soil pH and concentration of Ca ions in the soil [41].

3.7 Agricultural Management Strategies for Carbon Sequestration

Kundu et al. [42] pointed out that "while comparing different land use systems, grasslands store approximately 34% of the global terrestrial stock of carbon, forests store approximately 39% and agro-ecosystems approximately 17%". Thus, conversion of grassland or forest land system into agricultural systems harmed the soil carbon pools [43]. Therefore, different agricultural management strategies should be adopted for proper SOC storage which is important for sustaining soil productivity and protection from land degradation. Among these agricultural management strategies, tillage, fallow elimination, erosion control and methane mitigation in wetlands together reduce carbon loss, while crop management, nutrient management, land use systems, agroforestry and nanotechnology enhance carbon inputs into the soil [44].

Tillage- Carbon loss can be reduced by modifying the agricultural management practices like tillage, fallow elimination, erosion control and methane mitigation. Soil tillage affects SOC through its influence on both aggrading and degrading processes. Soil aggrading processes that enhance SOC are humification of crop residue and other biomass, increase in the resistant or non-labile fraction of SOC, sequestration of SOC by the formation of organo-mineral complexes, increase in stable aggregation, and deep placement of SOC in sub-soil horizons. In contrast, soil degrading processes having a negative impact on

SOC are erosion, leaching and mineralization [9].

Fallow elimination- Conversion from crop-fallow to more intensive cropping systems utilizing no-till is needed to enhance SOC sequestration. The negative C sequestration rate or C losses was reported to be much higher in the crop fallow system than continuous cropping and resulted in annual C losses of 62% to 66% [45].

Erosion control- "Erosion results in detachment of surface soil and exposes SOC that is physically protected within aggregates and clay domains; subsequently, finer soil particles and associated SOC are preferentially transported away from eroding slopes to different low-lying depositional sites. Following detachment and transport, burial usually is believed to protect SOC from decomposition, because there generally are enhanced old C stocks in the deep soils of agricultural lowlands and sedimentary basins. Erosion-induced deposition and burial maybe 0.4 to 0.6 Pg C yr^{-1} compared with 0.8 to 1.2 Pg C yr^{-1} emitted into the atmosphere" [3].

Methane mitigation- Methane emission from rice fields in India recorded a value of 2.92 Tg yr^{-1} in 2005 [46] and rice fields responsible for the production of 30% of global agricultural methane [47]. The emission of methane can be controlled by managing organic inputs and modifying irrigation practices. Cumulative amount of methane emitted (kg ha^{-1}) from soil can be reduced by incorporating rice straw compared to other organic sources such as FYM, green manure and wheat stubbles [48]. Intermittent drying in rice also reduces methane emission [49].

Crop management- To optimize the efficiency of C sequestration in agriculture, cropping systems such as intercropping, cover cropping and crop rotation play a critical role by influencing optimal yield, C sequestered within the biomass and that remains in the soil. Influence of diverse cropping systems viz., rice-rice-daincha and rice-rice-fallow on soil health and carbon pool at varying depths in a wetland riverine alluvial soil was studied by Chethankumar et al. [50]. The results showed that surface soils had higher SOC content and different carbon fractions compared to lower depths in all the cropping systems studied and higher SOC stock was reported in ecosystems having continuous cropping systems than fallow system. Greater C input with

increasing cropping intensity leads to greater SOC [51]. Cover crops exert a positive effect on C budget in sloppy areas not only through an increase in the C input but also by restricting C loss through erosion. The highest soil organic carbon content is found in slopes and flat areas subjected to cover crop management compared to conventional tillage [52].

Legume residue incorporation in cropping systems enhances the carbon sequestration rate [53-55] due to stabilization of non- labile carbon pool resulting in long term persistence of soil organic carbon. Mostly, grain legumes have a deep and robust root system which sequesters the C in a deep soil and the root exudates also act as carbon sources. The roots of legumes endowed with higher lignin-type compounds contribute to nonlabile C in soil with long residence time [56]. Inclusion of deep-rooted crops and Si- rich crops is beneficial in carbon sequestration. Most soil carbon is derived from roots rather than from shoots and leaf litter. The longer any particular form of carbon is held below ground before it is re-respired or emitted, greater the amount of carbon that can be sequestered in the steady-state [57,14].

Phytoliths - "Phytoliths are rigid, microscopic structures made of silica, found in some plant tissues and this hard silica encasement physically protects the encased organic carbon. The rates of phytolith production and the carbon occluded in phytoliths vary among the plant community and also within the community" [58]. "Agricultural plant species such as barley, maize, rice, sorghum, sugarcane and wheat were known to be prolific producers of phytoliths. The phytolith C bio-sequestration fluxes from millet, rice, wheat and sugarcane range up to 0.04, 0.13, 0.25 and 0.36 mg-e-CO_2 ha^{-1} year^{-1}, respectively" [42].

Nutrient management - "SOC concentration in the surface soil (0–15 cm) largely depends on the total input of crop residues on the surface or incorporated into the soil" [59]. Among the different methods of crop residue management, residue incorporation recorded the highest total carbon than residue removal/burning [60]. The carbon build up in soil treated with manure and chemical fertilizers in a long term fertilizer experiment was significantly higher under organic nutrient management. But the per cent share of slow carbon to total carbon was higher under INM. The contribution of the passive pool to total organic carbon was higher under both

permanent manurial trial and long-term fertilizer experiments [61]. Spaccini et al. [62] conducted an incubation experiment with 13C-labelled 2-decanol along with two humic acids from compost and lignite which had different hydrophobic properties and the results showed that higher the hydrophobicity of the employed humic material, the greater was the sequestration of organic carbon in the soil. Thermal decomposition of organic materials under little or no oxygen and at relatively low temperatures (<700 $^{\circ}$C), by the process of pyrolysis yields biochar which contains carbon mostly in the stable form [63]. Rajalekshmi and Bastin [65] pointed out that rice husk biochar showed a significant positive effect on soil organic carbon content in rice compared to other organic sources.

Nutrient management and greenhouse gas emission - Alluvione et al. [65] evaluated the greenhouse gas emission rate from different nitrogen fertilizer applied soils and reported that compost proved to be potentially suitable to reduce the CO_2 equivalent emission and N_2O emissions after soil incorporation than leguminous green manure, thereby reducing global warming. Similarly, biochar application had a significant influence on reducing CO_2 emission, compared to other organic amendments like FYM and vermicompost and also the rate of emission was almost constant which emphasize the stability of biochar C in soil (Fig. 4; [66]).

Land-use systems - The land use systems involving vegetable in Vellayani series (red loam soils), coconut in Amaravila series, rubber in Nedumangad (laterite soils) and Kallar series (forest soils), rice in Kazhakuttam series (coastal sandy soils) tea in Ponmudi series and homestead in Trivandrum series, significantly contributed to SOC addition [67]. In homesteads of Thrissur district, the relationship between plant species density and soil carbon sequestration was studied by Saha et al. [68] and results revealed that home gardens with high species density had the highest soil organic carbon per unit area (119.3 Mg ha^{-1}) and home gardens with medium and low species densities had comparatively 7 and 14% less soil organic carbon respectively. According to Dhanya [69] among the different land-use systems, rice and rice-fish contributed more passive pool of carbon towards total organic carbon, especially in Kallara series of acid sulphate soils.

Agroforestry- Carbon sequestration occurs in two major segments of the agroforestry ecosystem: aboveground and belowground. Aboveground C storage is the incorporation of C into plant matter either in the harvested product or in the parts remaining on-site in a living form and its potential is highly variable ranging from 0.29 to 15.21 Mg ha^{-1} yr^{-1}. The mechanism of the aboveground carbon sequestration is the uptake of atmospheric CO_2 during photosynthesis and transfer of fixed C into vegetation. Below ground carbon sequestration indicated carbon stored in soil organic matter and roughly two-thirds of the total carbon sequestration occurs belowground. The highest soil organic carbon content is recorded by forests followed by agroforestry systems, tree plantation and arable crops. The estimated soil carbon sequestration potential in agroforestry systems ranges from 2.72 to 18.9 Mg ha^{-1} yr^{-1} [16]. The transition from agriculture to agroforestry significantly increased SOC stock by 26 and 40% at 0–15 and 0–30 cm respectively [70].

Nanotechnology- "Nanotechnology is useful in developing nano-adsorbents with the high specific surface area for high retention of CO_2 in soil. Natural nanoparticles, *viz.* nanoclays, hydrous Fe oxides, or oxyhydroxides have been documented for their plausible effects on carbon stabilization in soil. The uniqueness of nanoparticles in respect of their electronic, magnetic, kinetic, and optical properties has been attributed to enhance carbon stabilization in soil" [1].

3.8 Carbon Stabilization Mechanisms under Different Management Strategies

- ***Conservation tillage*- "**Conversion of native vegetation to conventional tillage disrupts soil aggregates, promotes the dispersion of clay particles and silt + clay microaggregates, and diminishes the formation of new aggregates. However, during conservation tillage, micro aggregates coalesce together to form macroaggregates in the presence of organic residues and microbial polysaccharides. These stable macroaggregates physically protect a considerable proportion of organic matter from microbial decomposition within it through compartmentalization, making them inaccessible to microbes for decomposition. Thus C-rich macro-aggregates increased and the amount of C-depleted micro aggregates decreased during conservation tillage compared to conventional tillage" [71].

- ***Deep-rooted crops*- The mean residence time in soils of root-derived C is 2.4 times that of shoot-derived C. Stabilization of root-derived SOM than shoot derived carbon is due to the chemical recalcitrance of root tissues, inputs of carbon compounds into the rhizosphere through exudation, physico-chemical protection in deeper horizons, micrometre-scale physical protection through mycorrhiza and root-hair activities, and chemical interactions with metal ions [72].
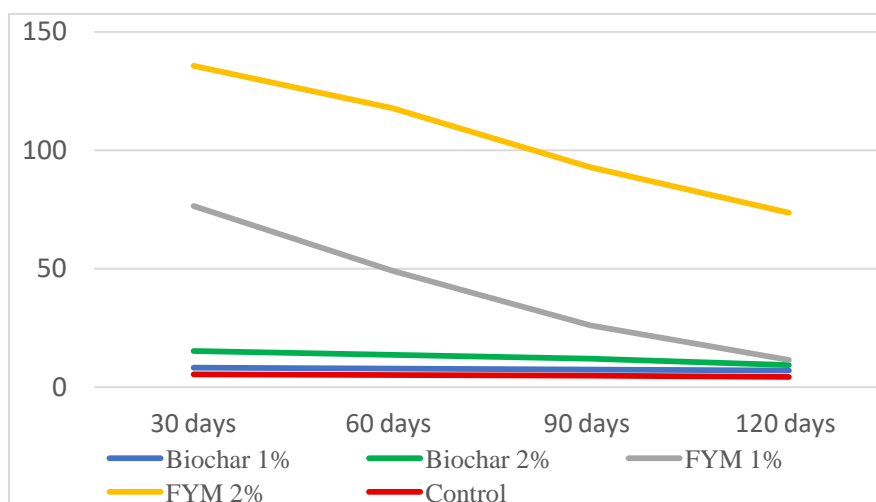

Fig. 4. Carbon dioxide emission by different manures [64]

"Plant roots contribute to the formation of stable aggregates and improve aggregate stability through different mechanisms: (i) increased production of root exudates which act as a glue between soil particles, (ii) soil particle trapping facilitated by the entanglement of roots and hyphae, (iii) increased wetting-drying cycle frequency in the soil in relation to water acquisition by roots, (iv) input of plant residues that contribute to macroaggregate stability and (v) stimulation of the production of microbial metabolites involved in microaggregate stability" [73].

- *Phytolith-occluded carbon (PhytOC)*- Phytoliths are formed through the process of biomineralization in the tissues of plant leaves and stems. PhytOC is highly resistant to decomposition and persists in the soil environment for a long period and is known as plant opal or plant stones. After crop harvest, PhytOC in the straws/stovers find its way to the soil. About 50% of total biomass produced from, crops such as barley, maize, rice, sorghum, sugarcane and wheat finally reaches the soil through residue incorporation, in addition to the wastes after feeding the animals, animal excreta, farmyard manure in the form of compost and burned ashes [74], thereby a substantial amount of PhytOC reaches the soil.

- *Compost*- The application of compost high in phenolic and lignin residues was found to accelerate the accumulation of lignocelluloses and hemicelluloses in comparison with inorganic fertilizers, resulting in a decrease in the mineralization rate per unit of SOC. From the long-term trial conducted by Favoino and Hogg [75], it was concluded that continuous use of compost manure resulted in twice the SOC content than chemical fertilizers and suggested that a particular proportion of the readily available organic carbon in compost being mineralized is converted to stable organic matter. Of this stable organic matter, some carbon is mineralized, but at a much lower rate than the rate of formation of resistant organic matter.

The carbon in compost can be stabilized by the addition of clay minerals which decrease the rate of decomposition, thereby increasing the stabilization of C. Bolan et al. [76] observed that the half-life for poultry manure compost increased from 139 days to 620, 806 and 474 days with the addition of goethite, gibbsite and allophane respectively. The increase in the stabilization of C with the addition of clay materials may be attributed to the immobilization of C, thereby preventing it from microbial decomposition. Stabilization of C in compost using clay materials did not impact negatively the value of composts in improving soil quality.

Humic substances- Labile materials used as organic soil amendments will contribute more to SOC storage and sequestration over a short term. Alteration of the original chemical compounds in plant residue occurs through microbial attack and decomposition, after which condensation and polymerization occur at mineral surfaces. The amendments reaching sequestered status as humic materials and the rate of this transformation depends upon the chemical composition of the material, C:N ratio, soil properties, and environmental factors such as temperature and water [77].

Clay humic complexes- The organic molecules of compost can be adsorbed to the clay minerals by polyvalent cations. Organic anions of C-rich humic colloids and polysaccharides are adsorbed by clay particles through polyvalent metals. These complexes occur within clay domains forming clusters of micro aggregates and are protected from microbial decomposition. The strength of bonds depends on the valency of the metals bridging the inorganic and organic anions following the order: $Al^{+3} > Fe^{+3} > Ca^{+2} > Na^{+}$. Formation of clay-humic complexes subsequent to compost addition and decomposition is controlled by bonding mechanisms such as H-bonding, van der Waal's forces, and Coulombic attractions. These organo-mineral complexes stabilize C through three critical physical and biochemical functions: (i) organic materials react with clay particles through adsorption, (ii) clay surfaces polymerize humic substances and (iii) the polymerized organic compounds are physically and chemically sequestered by clay crystals inaccessible to soil organisms [78]. The rate of C stabilization depends on the surface area, ionic charge, type, and chemical and geochemical composition of clay minerals. Smectite-dominated clay favoured a greater SOC storage than kaolinite- and chlorite-dominated clay minerals [78].

- *Biochar*- Conversion of biomass C into biochar C leads to sequestration of about

50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (<10–20% after 5–10 years), thus yielding more stable soil C than burning or direct land application of biomass. Biochar has twofold higher carbon content than ordinary biomass. About 50% of the biomass is pyrolyzed and converted into biochar and can be returned to soil [79].

Lignin, cellulose and hemicellulose in the plant residue are converted to many allotropes of carbon especially graphite crystals *viz.,* hexagonally-shaped carbon rings, with some leftover hydrogen and oxygen attached, along with some minerals and constitute the skeletal structure of biochar. These hexagonal carbon compounds are fused to form aromatic carbon which are very stable and hence microbes take a long time to degrade them. More fused carbon rings are created with more heating of biomass. The rings hook up with each other to form layers and layers of discontinuous, rumpled sheets. Biochar become more mineral-like with heating which are hardly biodegradable and thus the carbon gets protected in the skeletal structure of biochar [80].

The presence of biochar in soils actively promotes the formation of aggregates through a greater abundance of fungal hyphae. Biochar is also able to serve as a habitat for extraradical fungal hyphae that sporulate in their micropores due to lower competition from saprophytes. Soil texture also plays an important role in biochar's stability. Biochar is highly stable in soils rich in clay particles due to its large surface area [63]. The inherent characteristics of biochar such as feedstock type and pyrolysis conditions interact with climatic conditions to influence how long biochar carbon remains stored in the soil. Stability of biochar depends on the production procedure. Shorter pyrolysis time and higher pyrolysis temperature yields more recalcitrant biochar.

- *Agroforestry*- The effect of agroforestry due to changes in quantity and quality of litter inputs, humification, and aggregation and translocation of biomass into the subsoil by root system enhances soil carbon storage. Land-use conversion from forests to agroforestry decreased the SOC stocks due to lack of diversification, density, and structural complexity of the land-use systems. The conversion assisted with soil aggregate breaking, soil structure deterioration and disruption of physical protection provided by vegetation coverage also inversely affected soil organic carbon storage. Conversion from cropland to systems with trees have a positive effect on SOC *via* higher inputs, deeper deposition, and reduced decomposability of OM. Moreover, agroforestry reduces tillage and soil disturbance regimes, which can help to maintain or even increase SOC pools [14].

- *Nanotechnology-* Nano-zeolite, nano-ZnO particles, and nano-Fe particles effectively increase the mean weight diameter of water-stable aggregates of soil and organic carbon content in each aggregate size fraction. The high Ca content in zeolite mineral is responsible for the formation of cation bridges between organic matter and clay crystals, thus protecting them from decomposition. Nano-ZnO and Fe have been reported to induce the secretion of extracellular polysaccharides from microbes thus forming stabilized carbon. The electronic, magnetic, kinetic, and optical properties of nanoparticles also enhance carbon stabilization. Nanotechnology is useful in developing nano-adsorbents with the high specific surface area for high retention of CO_2. Carbon nanotubes and nanotubes functionalized with amines by physical adsorption processes can be used for removal of CO_2. Single-walled carbon nanotubes and multiwalled carbon nanotubes show the high capacity of adsorbing CO_2 due to activated carbon. CaO derived from nano-sized $CaCO_3$ was also reported as a potential CO_2 absorber. Thus soil is a potential source of natural nanoparticles having the capacity to stabilize SOC for a long term [1].

4. CONCLUSION

Rise in carbon dioxide (CO_2) emissions is a major cause of global warming. Elevated atmospheric temperature leading to global warming can be minimized by reducing the emission of CO_2 into the atmosphere. This can be achieved through carbon sequestration activities. Soil especially managed agricultural soils, have the potential to store (sequester) carbon (C) and contribute to the mitigation of GHG emissions.

Improvement in soil organic carbon content through judicious soil and crop management, appropriate land use, and science-based improved agriculture enhances soil quality. The judicious soil management practices also stabilize carbon in the soil for a long term. Management of soil organic carbon, therefore, is crucial to high soil quality and attainment of agricultural sustainability.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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