Egypt. J. Soil Sci. **Vol. 64**, No. 2, pp: 581 - 598 (2024)

Egyptian Journal of Soil Science

http://ejss.journals.ekb.eg/

Carbon Sequestration through Organic Amendments, Clay Mineralogy and Agronomic Practices: A Review

Shivangi[1], **Omkar Singh**[1]; **Uday Pratap Shahi**[1]; **Praveen Kumar Singh**[1]; **Abhishek Singh**[2]; **Vishnu D. Rajput**[3]; **Tatiana Minkina**[3]; **Hassan El-Ramady**[4]* and **Karen Ghazaryan**[2]

[1]*Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut-250110 Uttar Pradesh, India*
[2] *Faculty of Biology, Yerevan State University, Yerevan, Armenia*
[3] *Academy of Biology and Biotechnology, Southern Federal University, Rostov on Don, Russia*
[4]*Soil and Water Dept., Faculty of Agriculture, Kafrelsheikh University, Egypt*

CARBON sequestration (CS) is a significant method for reducing climate change (CC) and enhancing soil fertility in agriculture. Many people are becoming increasingly worried about climate change, and researchers have been studying soils as a way to store CO_2. Due to their significance in regulating the global carbon cycle, the methods of soil organic carbon (SOC) stabilization have recently garnered considerable interest. SOC dynamics, focusing on how clay mineralogy affects soil retention and stabilization. Understanding how SOC stabilization works can help in implementing effective management practices for storing soil organic matter (SOM), improving soil structure, and reducing greenhouse gas emissions. The effectiveness of SOC sequestration depends on the amount and quality of SOM, soil type, topography, mineral type, and CC. Soil carbon has been lost as a result of inadequate crop and soil management strategies. Over the world, 456 Pg of soil carbon is stored in dead organic matter and above-ground vegetation, compared to 1417 Pg in the first meter of soil. The agricultural sector is accountable for 25-30% of total worldwide greenhouse gas (GHG) emissions in the form of CO_2, N_2O, and CH_4. Soils that have a lot of organic matter can store more CO_2, hence having healthy soils can assist in combating climate change. In addition, to sequester SOC, it is important to use organic materials like manure, minerals found in soil, different types of compost, poultry waste, incorporating leftover plant parts, biochar, and proper farming methods like covering the soil with mulch, planting cover crops, managing nutrients, and using mulch effectively. These methods help increase the amount of organic matter in the soil, improve its physical and chemical characteristics, and help the soil store more carbon, which ultimately helps with carbon sequestration and mitigating climate change.

Keywords: Climate Change, Clay Mineralogy, Carbon Sequestration, Soil Fertility, Soil Organic Matter.

1. Introduction

One of the primary concerns today is making sure that there is enough food and nutrition for a growing population affected by climate change. The rise in temperature, unpredictable rainfall patterns, and severe weather events all show how climate change is impacting our ability to ensure sufficient food (ElGhamry et al. 2024). The worldwide average temperature is projected to increase by 1.5 °C over the period before industrialization between 2030 and 2050. (IPCC, 2022). The decrease in natural resources, the level of pollution, and the deterioration of the land are all worsened by the adverse impacts of climate change. The consequences of climate change and the limitations of food production systems pose an imminent threat to the livelihood and food security of millions of people. Agriculture, while providing various benefits to the environment, also contributes to global warming through the release of greenhouse gases.

The balance between organic C inputs into the soil (from agricultural wastes, compost that contains organic material, manure from animals, etc.) and organic C decomposition by soil microbes is known as net SOC sequestration (Das et al. 2023). The relationship between annual carbon intake and the rate of soil organic carbon accumulation, which

---

*Corresponding author e-mail: ramady2000@gmail.com
Received: 04/01/2024; Accepted: 11/02/2024
DOI: 10.21608/EJSS.2024.260719.1707

serves as a measure of soil organic carbon sequestration ability, is a standard method for expressing the efficacy of SOC sequestration (McLauchlan 2006). To find high-efficacy management strategies to enhance soil health and SOC stock, understanding of the C sequestration efficiency is helpful (Hua et al. 2014). The largest carbon store in terrestrial ecosystems, soil, must be sequestered to affect the global climate (Salehi et al., 2017; L. Wu et al. 2021). Yet, when woods or grasslands are converted to agricultural land, the soil organic C (SOC) concentration decreases by 30–80%. (Frey et al. 2014). The quantity of carbon (C) retained in soils is crucial on a worldwide scale because soil carbon capture reduces the CO_2 in the atmosphere load and plays a major part in the worldwide C budget (Eshel et al., 2007).

Though traditional agricultural methods contribute to food availability, they also frequently result in inappropriate input consumption, higher emissions of greenhouse gas, and resource degradation. Moreover, using intense farming techniques and cultivating damaged land led to the loss of carbon from the soil as well as other crucial nutrients (Lal, 2015; Fang et al., 2018). As a result, it impairs soil fertility and renders it unusable for future farming. Soil organic matter must be increased on agricultural fields to improve soil fertility and productivity and reduce greenhouse gas emissions. Many studies have shown that soil organic matter boosts crop output by maintaining soil health and having a positive effect on the soil's quality and functioning (Lal, 2015; Manlay et al., 2007). Crop rotation, organic amendment, intercropping, and agroforestry are other methods that have been shown to increase soil carbon supply. Also, the Intergovernmental Panel on Climate Change (IPCC) acknowledges these better management techniques as a significant soil management approach to handle worldwide climate change challenges successfully (IPCC, 2019).

Day by day, several published studies on soil carbon sequestration and its potential against climate change (Luo et al. 2023; Phillips et al. 2023; Wang et al. 2023; Wang and Kuzyakov 2023; Zhang T. et al. 2023; Zhang W. et al. 2023; Pan et al. 2024; Zhu et al. 2024).

Therefore, this review focuses on soil carbon sequestration and its potential. Organic amendments, clay mineralogy, and agronomic practices will be discussed, and their roles in soil carbon sequestration. The strong relationship between climate change and soil carbon sequestration will be also highlighted.

2. Carbon Sequestration through Organic Amendments

Organic soil additives are a practical strategy to boost C retention and enhance soil aggregate formation (Powlson et al. 2014; Wang et al. 2015). The soil C content is raised through additions such as compost, crop straw, organic manure, and bio-gas leftovers (Zhu et al., 2015; Yang et al., 2017). Due to their affordability and simplicity, crop straws and organic fertilizers are frequently used. A prior study found that rotating productive agricultural grazing grassland considerably raised SOC in the 0-150 cm soil layer throughout a 20-year trial by about 70%. (Schiedung et al., 2019).

Organic alterations help sequester carbon through several different processes. First, these amendments increase the amount of organic matter in the soil, which acts as a carbon storage space. When organic matter breaks down, carbon dioxide is released into the atmosphere. The rate of carbon input, however, surpasses the rate of decomposition when organic amendments are added to soil, creating a net carbon sink. Second, organic amendments improve the structure of the soil and boost its capacity to hold water and nutrients, which fosters plant growth. Through photosynthesis, this additional plant biomass adds to the carbon sequestration process (Figures 1 and 2).

By raising crop biomass from root systems, which improves SOC sequestration and the creation of soil aggregates, restoring straw has the potential to increase resistant C inputs as well (Li et al., 2019). Biochar generated from agricultural waste is another intriguing addition for boosting soil quality and carbon storage (Wang et al., 2017a, Wang et al., 2017b, Woolf et al., 2010, Li and Delvaux, 2019). It has been demonstrated that applying biochar reduces soil bulk density and increases porosity in semi-arid regions.

In addition, biochar can alter soil structure and stability by interacting with SOC, microorganisms, and minerals (Li et al. 2018). Numerous studies have shown that organic additions considerably boost soil carbon reserves. For instance, a meta-analysis published in 2015 by Poeplau and Don titled "Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis" revealed that the use of cover crop systems enhanced soil organic carbon stocks by an average of 0.83 tonnes per hectare per year. Enhancing Nutrient Availability and Soil Fertility: Organic amendments boost nutrient availability and soil fertility, which increases plant productivity.

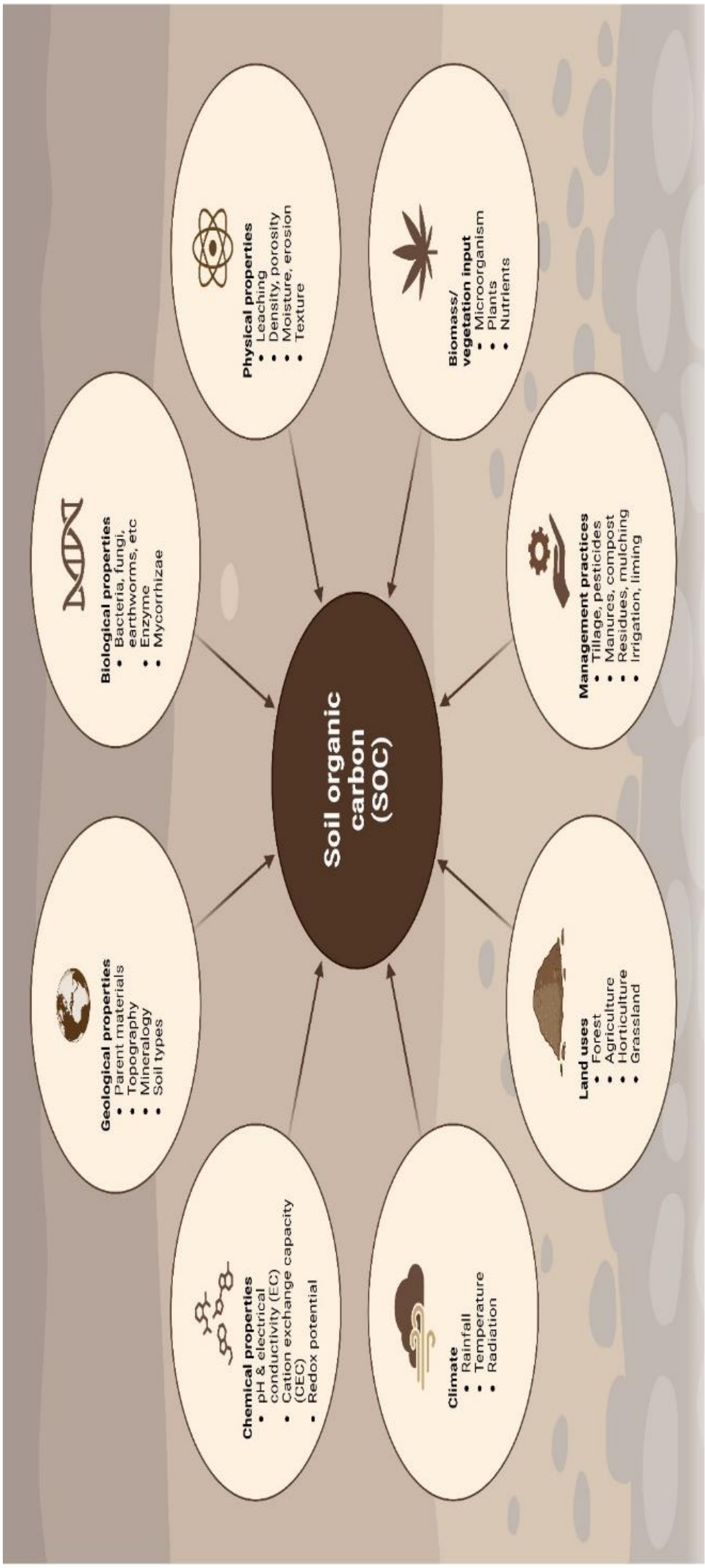

Fig. 1. The figure demonstrated shows the role of soil organic carbon in earth life (source: made by authors).

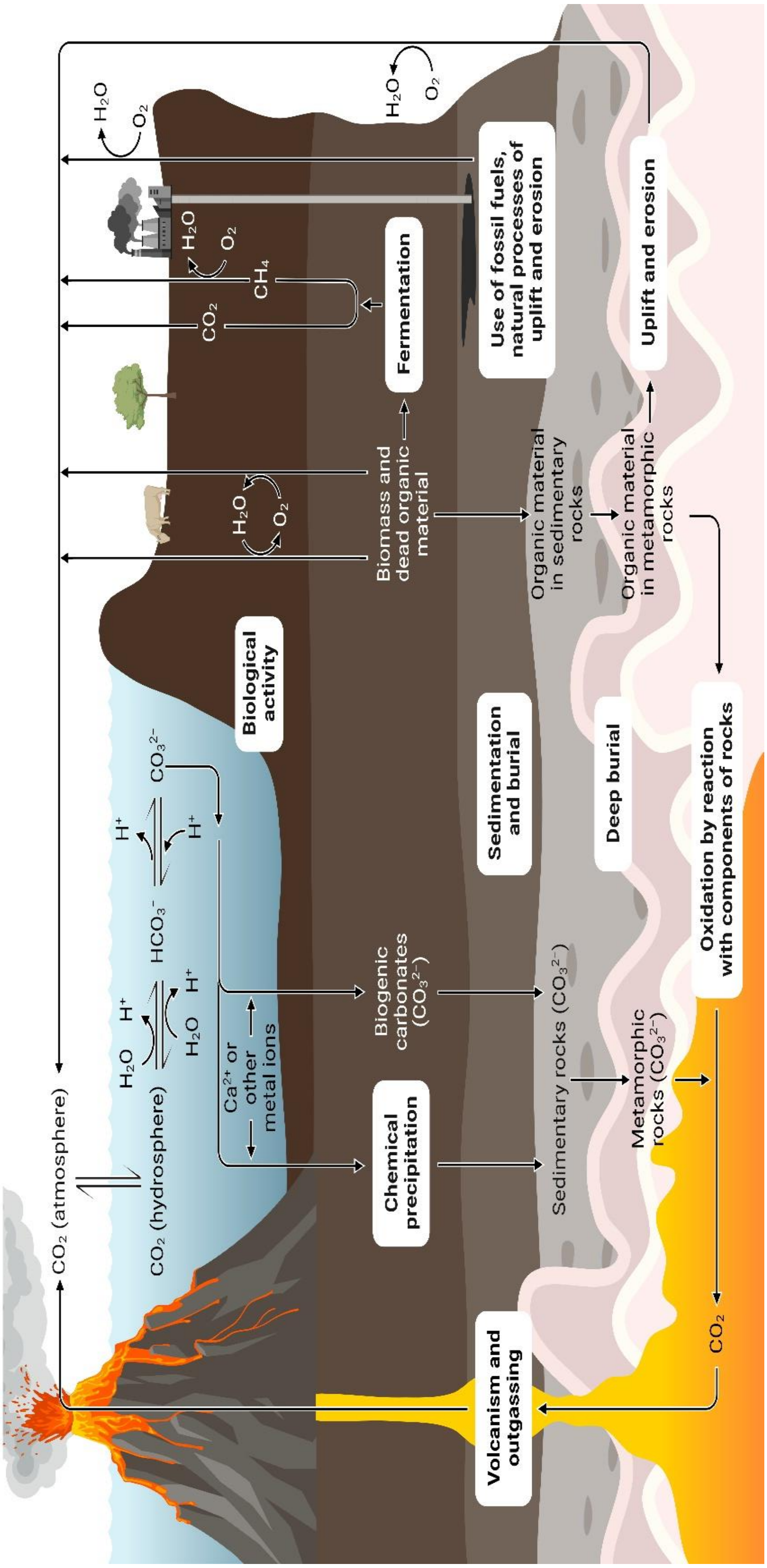

Fig. 2. Diagrammatic presentation of carbon cycle (source: made by authors).

According to a global research, biochar has the ability to remove 0.03-6.6 Gt CO_2e each year from the atmosphere (IPCC, 2019). Moreover, organic fertilizers boost soil organic matter content, enhance soil aggregate stability, and preserve soil microbial biomass (Wang et al., 2017a, Wang et al., 2017b). Also, there are significant differences in the chemical and structural makeup of the biomass in straw, biochar, and organic fertilizer (Wu et al., 2019). To get insight into SOC fluctuations under various organic amendment regimes, it is possible to better understand the bonding position of the Carbon framework in the surface layers of soil particles (Elbasiouny & Elbehiry 2019; Wen et al., 2019). An investigation by Verhoeven et al. (2019) titled "Biochar reduces the nitrogen footprint of cropping systems" revealed that biochar amendments in agricultural areas decreased N_2O emissions by up to 50%, assisting in the mitigation of global climate change.

Due to the high background concentrations, SOC modifications in soil often take place gradually and are challenging to evaluate (Beare et al., 1997). Low conversion intervals exist between fresh crop residues and stabilized organic material for the labile SOC fractions of the organic amendment (Chen et al., 2016). The labile components include permanganate-oxi-disable fractions ($KMnO_4$-C), particulate organic fractions (POC), dissolved organic fractions (DOC), and microbial biomass (MBC) (Liang et al., 2012). To preserve and improve organic soil C in salty soils, it is crucial to understand how labile soil organic fractions fluctuate in response to various organic amendments. But, via the use of sustainable agricultural methods, agriculture also serves as a natural carbon sink and offers a significant chance to trap atmospheric carbon. Finding farming methods that increase carbon sequestration without compromising other ecosystem benefits is therefore essential. To optimize the opportunity for the storage of carbon on land used for agriculture, a plan named "4 per 1000" was also begun. Its goal is to enrich soil organic carbon by 0.4% annually. (Nath et al., 2018; Lal, 2020b).

Integrated management of nutrients, biological reforms, no-tillage, crop succession, residue retention, intercropping, biochar, and agroforestry are the most well-known SAPs to promote carbon sequestration on cultivated soils. Recent years have seen a rise in the use of these procedures because of increasing recognition of the significance of SAPs and field-level evidence (Clark et al., 2017; Chen et al., 2009). After harvesting, conserving residue in the soil enhances moisture levels, soil quality, and carbon sequestration (Turmel et al., 2015). Moreover, applying biochar enhances soil stability and slows down the pace of degradation (HanWeng et al., 2017).

2.1 Organic amendments

i. Animal manure

Animal manure can be used to raise soil organic carbon (SOC) levels, which can result in carbon sequestration when managed properly. The majority of animal dung's potential for sequestering carbon is derived from its capacity to improve soil health, accelerate nutrient cycling, and increase soil storage of organic carbon (Gross et al. 2021; Roß et al. 2022). By adding organic matter, manure acts as a soil conditioner, enhancing the soil's structure and capacity to store water. This encourages the growth of roots, uptake of nutrients, and overall productivity of plants (Liang et al. 2021).

Moreover, adding manure improves soil aggregation, reducing carbon loss from erosive processes. This enhanced absorption of carbon not only enhances soil health but also reduces atmospheric CO2 levels (Huang et al. 2022), which assists in the struggle against climate change.

Animal excrement is the source of carbon, and it has an impact on carbon concentrations in different agricultural fields (Stewart et al. 2007). Although the average yearly carbon sequestration rates over three long-term (>49) years of animal manure use varied between 10 to 22 kg C ha^{-1} yr^{-1} t^{-1} of dry solids, Powlson et al. (2014) reported that soil organic carbon sequestration rates with a shorter-term investigation (8-25 years of manure from farms, cattle slurry, and boiler litter) ranged from 30 to 200 kg C ha^{-1} yr^{-1} t^{-1} of dry solids. Utilizing animal manure's capacity for carbon sequestration offers a practical route to sustainable agriculture and climate change mitigation. Manure management practices provide a win-win situation for farmers, the environment, and the global climate by strengthening soil health, enhancing nutrient cycling, and increasing soil organic carbon storage. The advantages of animal dung in carbon sequestration can be maximized by using proper manure management techniques and implementing sustainable farming practices. However, to improve manure management practices and encourage their widespread adoption, more study and technical development are required.

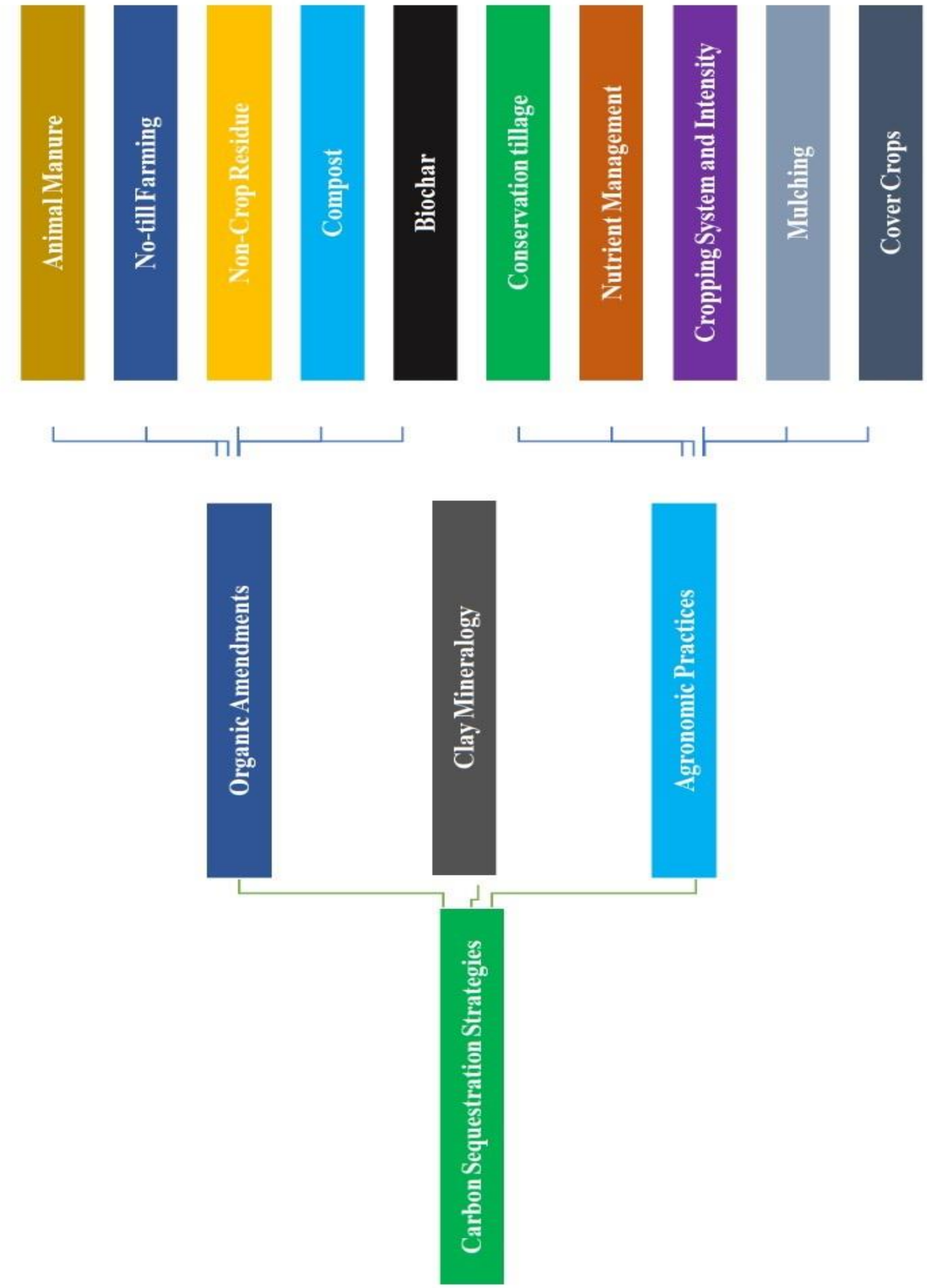

Fig. 3. Different carbon sequestration strategies (source: made by authors).

ii. Crop residues

Crop residues are a great source of organic carbon and can be used to replace agricultural soils' organic matter levels. Crop leftovers decompose after being absorbed into the soil, which aids in the accumulation of soil organic matter (**Table 1**). In turn, this improves soil fertility, increases water-holding capacity, and encourages nutrient cycling, resulting in an environment that is favourable for plant growth (Hussein et al. 2022). Due to their affordability and simplicity, crop straw and organic fertilizers are frequently used. A prior study found that after flipping highly productive grazing grassland, SOC in the 0-150 cm soil layer grew dramatically throughout a 20-year study by about 70% (Schiedung et al. 2019). By boosting crop root biomass, which increased SOC sequestration and soil aggregate formation, straw returns could potentially increase more recalcitrant C inputs (Li et al. 2019).

Crop residue output is considerably increased by the intensive agricultural system. This could improve soil aggregation and SOM, which would boost C storage (Schiedung *et al.* 2019). The composition of agricultural residue affects how quickly it degrades. For instance, it is challenging for microbes to begin the breakdown of compounds with a high lignin content. Chemical, metabolic, and physical stabilization are the three methods that have been categorized based on the stabilization of SOM (Christensen *et al.* 2001). Through integrated nutrient management, agricultural practices including the addition of crop residues raise the SOM and nutrient levels of the soil (Fang *et al.* 2018).

Utilizing crop leftovers' capacity to store carbon is an important possibility for climate change mitigation and sustainable agriculture. Crop residues help to build resilient farming systems by increasing soil organic matter, enhancing soil health, and lowering greenhouse gas emissions. The advantages of crop residues in carbon sequestration can be maximized by putting into practice suitable residue management procedures and adopting sustainable agricultural practices. To maximize the potential for crop residues to sequester carbon in a variety of agricultural systems, more research and the dissemination of best practices are necessary.

Table 1. Potential of Soil Carbon Sequestration by Crop Residues.

Crop	Potential for Soil Carbon Sequestration	Refs.
Wheat	Increased SOC by 11% over 10 years with straw application	Wang et al. (2015)
Rice	Increased resistant carbon inputs and aggregation	Li et al. (2019)
Maize	Increased labile SOC fractions with stover application	Yang et al. (2017)
Sugarcane	Increased total SOC by 17% in 9 years with trash retention	Meier et al. (2021)
Soybean	Increased particulate and mineral SOC fractions	Loss et al. (2020)
Potato	Increased SOC stocks by 1.4 Mg/ha in 2 years with haulms	Padbhushan et al.(2021)
Barley	Straw incorporation increased SOC by 0.62 Mg/ha/yr	Kirkby et al. (2014)
Oat	Straw return increased SOC by 0.12-0.2 Mg/ha/yr	Kirkby et al. (2014)
Rye	Increased SOC in top 20 cm by 14% with straw	Koga & Tsuji (2009)
Tomato	Shoot incorporation increased SOC by 1.5 Mg/ha in 5 months	Nouri et al. (2019)
Cotton	Shredded stalks increased total and labile SOC	Liu et al. (2014)
Peanut	Haulms increased SOC by 1.2% over 4 years	Reddy et al. (2007)

iii. Compost

The conversion of organic waste into nutrient-rich soil amendments by composting is a natural process. The regulated and deliberated decomposition of various organic materials, such as manure from animals, hardwood material, and other natural waste, is known as composting. Composting is widely recognised for its capacity to keep trash out of landfills and improve soil fertility, but it also has a significant impact on carbon sequestration. Composting offers a long-term method of reducing climate change by boosting the capture and storage of carbon dioxide (CO_2) from the atmosphere (Elsherpiny, 2023). In the process of composting, plants can absorb the C content. In mature compost, humic compounds account for 50% of the accessible carbon (Inbar *et al.* 1990) and are assumed to be more practically stable. In the compost application, a mean of 60 kg C ha^{-1} yr^{-1} t^{-1} of dry solids was measured over an extended period of approximately

8 years or 5 years. (Wallace, 2007). According to Gregorich et al., (2001) decomposition can capture up to 50% of the carbon that was initially present in the feedstock, lowering the release of CO_2 (**Table 2**). Compost contains humic compounds including humic and fulvic acids that bond to soil minerals and increase carbon's resistance to microbial breakdown. According to a study by Zhang et al. (2023), soils that have been modified with compost have higher carbon stability and lower rates of carbon mineralization. By removing and storing carbon dioxide from the atmosphere, composting is an essential part of the carbon sequestration process. Composting provides a sustainable route to combat climate change through organic matter decomposition, increased soil organic carbon, soil carbon stabilisation, decreased nitrous oxide emissions, and landfill diversion. Composting techniques can be applied at both the individual and industrial levels to greatly reduce carbon emissions and fight global warming.

iv. Biochar

Biochar, a form of charcoal produced by the pyrolysis of biomass, has become well-known for its potential to store carbon. By absorbing carbon dioxide (CO_2) from the atmosphere and providing long-term storage in soils, biochar offers a sustainable option to combat climate change. Amazingly, biochar can hold carbon for long periods. Biochar resists microbial decomposition due to its high aromaticity and refractory character, resulting in long-term carbon storage in soils (Elsherpiny, 2023; Luo et al. 2023). A study by Lehmann et al. (2006) showed that biochar is stable for periods of hundreds to thousands of years, making it a trustworthy approach for carbon sequestration. According to Jeffery et al. (2017)'s meta-analysis, biochar-amended soils had significantly higher SOC levels than unamended soils. SOC serves as a carbon storage area, lowering the levels of CO_2 in the atmosphere. According to a study by Singh et al. (2023), soils treated with biochar emit considerably less N_2O than unamended soils. By serving as a physical barrier, the adsorption capabilities of biochar can aid in lowering CH_4 emissions from paddy fields (Saikanth et al. 2023).

Table 2. Effect of organic amendments on soil carbon sequestration.

Organic Amendment	Effect on Soil Carbon Sequestration	Details	Ref.
Animal manure	Increased SOC levels by 10-22 kg C ha/yr/t of dry manure solids	Long-term application (>49 years) increased SOC storage rates	Stewart et al. (2007)
Crop residues	Increased SOC by 70% over 20 years in grassland	Flipping highly productive grazing grassland increased SOC in 0-150 cm layer	Schiedung et al. (2019)
Compost	Increased SOC stocks by 60 kg C ha/yr/t of dry compost solids	Application over 8-5 years increased SOC stock	Wallace, (2007)
Biochar	Increased SOC stocks compared to unamended soils	Meta-analysis showed higher SOC in biochar amended soils	Jeffery et al. (2017)

Due to its capacity to stabilize and hold carbon in soils for extended periods, biochar presents a promising method for sequestering carbon. Biochar makes a substantial contribution to the fight against climate change by increasing soil organic carbon, encouraging nutrient retention and plant growth, lowering greenhouse gas emissions, and keeping organic waste out of landfills. Biochar's full potential as a useful instrument in carbon sequestration can be unlocked with more study and extensive application of its practises.

2.2 Carbon sequestration through clay mineralogy

While several natural and artificial processes help to sequester carbon, attention has recently focused on the part clay minerals play in this process (**Table 3**). The common clay minerals found in soil and sedimentary systems have special qualities that allow them to interact with and store carbon. Because of their large surface area and lattice structure, clay minerals can physically shield and stabilize organic carbon (El-Demerdash et al. 2022). The adsorptive ability of clay minerals enables them to hold onto organic matter and stop it from decomposing, extending the time that carbon spends in soils. Clay minerals significantly shield soil organic carbon from microbial deterioration, boosting its long-term stability and sequestration potential, according to studies by Angst et al. (2016).

The development of soil aggregates, which are essential for carbon sequestration, depends on clay minerals. Clay minerals combine to form aggregates that physically enclose biological carbon inside their framework. Additionally, these aggregates offer microenvironments that are ideal for carbon stabilization. The role of clay minerals in the development of durable soil aggregates and the sequestration of carbon was highlighted in studies by Six et al. (2004).

Carbon is stabilized as a result of interactions between minerals and organic matter that clay minerals enable. Clay minerals bond organic carbon molecules through mineral-organic interactions, which makes them less accessible to microbial deterioration. These interactions involve procedures including the creation of organo-mineral complexes and the encapsulation of organic carbon by minerals.

A conceptual hierarchical model for aggregate development and stabilization in temperate soils was presented by Tisdall and Oades in 1982. According to their model, the three types of organic matter—persistent, transient, and temporary—are related to the three types of soil physical units—clay and silt, micro aggregates less than 250 m, and macro-aggregates greater than 250 m. According to Denef et al. (2004), cultivation typically reduces the stability & quantity of macroaggregates but has no effect on the longevity of micro aggregates (Tisdall and Oades, 1982). As a result, it has been suggested that the primary source of organic matter lost during agriculture is the soil organic matter that connects micro aggregates into macro aggregates (Elliott, 1986).

The results of Das et al. 2023 demonstrated that Mollisol and Vertisol, which were dominated by kaolinite + illite + chlorite-interstratified minerals and smectite/2:1 interstratified mineral, respectively, had the maximum cumulative C mineralization (CO_2-Ccum). Next came the kaolinite- and illite-dominated Alfisol and Inceptisol. According to the percentage of SOC loss, Mollisol and Vertisol lost the least amount of SOC (10.1%), while Inceptisol and Alfisol lost the most (9.02%). In terms of labile C fractions and dehydrogenase activity, Mollisol and Vertisol performed much better than Alfisol and Inceptisol. Cation exchange capacity (CEC) and specific surface area (SSA) have negative correlations with % SOC and positive correlations with C mineralization and labile C fractions, respectively.

Table 3. Role of clay minerals in carbon sequestration.

Clay Mineral	Role in Carbon Sequestration	Details	Refs.
Kaolinite, illite	Lower carbon stabilization compared to smectite and interstratified clays	Highest SOC (%) loss indicating lower stabilization	Das et al. (2023)
Smectite, interstratified clays	Higher carbon stabilization due to CEC, SSA	Lowest SOC (%) loss indicating higher stabilization	Das et al. (2023)
Amorphous minerals	Positively correlated with soil organic carbon	Significant positive correlation with TOC in fine and coarse clay fractions	Chatterjee et al. (2013)

Ferro et al. (2023) reported that macroaggregates (>250 mm) and microaggregates (250 mm) exert physical SOC protection (Six and Paustian, 2014). For a very long time, the development of soil aggregates, particularly macroaggregates (Lehmann et al., 2017), has been linked to fungal populations, both saprophytic and mycorrhizal, as well as their hyphae and exudates (for example, glomalin linked to arbuscular mycorrhizal -AM- fungi) (Ritz and Young, 2004). Because of the limited accessibility, the SOC contained in aggregates is physically protected, which slows down the phenomenon of SOC degradation (e.g., oxidation, microbial attack). The level of soil aggregation, which determines the arrangement of soil particles and the complexity of soil pores, establishes a maximum SOC storage capacity at which OC is not physically protected (Six and Paustian, 2014). These results show that the quantity of SOC that can be protected in bulk soil is constrained. It is influenced by both the inherent soil characteristics of various soil types as well as soil and land management practices (Guo et al., 2020; Stewart et al., 2007), which can either preserve or degrade soil structure or contribute to OC inputs.

Due to its distinct characteristics and interactions with organic matter, clay mineralogy offers a fresh method for sequestering carbon. Clay minerals make a substantial contribution to carbon sequestration efforts through physical protection and stabilisation, carbon sorption and sequestration, aggregate formation and carbon trapping, mineral-organic interactions, and the reduction of soil acidity. Understanding and utilising clay mineralogy's potential can result in long-lasting solutions for climate change mitigation. To maximize the use of clay minerals in different soil types and ecosystems and to realize the full potential of these minerals in carbon sequestration, more study is required.

2.3 Carbon sequestration through agronomic practices

By collecting carbon dioxide (CO_2) from the atmosphere and storing it in long-term reservoirs, carbon sequestration is an essential tactic in combating climate change. Agronomic practises can have a big impact on carbon sequestration, which also involves natural ecosystems in a big way.

The following are only a few of the various goals of soil carbon sequestration: restoring the health of the soil and its related ecosystem functions and services; reducing emissions from human activity from burning fossil fuels and lowering the net increase in atmospheric CO_2 concentration (which reached 400 ppmv in 2013) and pool (800 PgC). fostering the development of environmentally friendly soils and agroecosystems, improving the disease-fighting capabilities of the soil, boosting agronomic production, improving the security of food and nutrition, and improving the soil's capacity to retain water and nutrients. enhancing the efficiency with which soil uses inputs reducing the dangers of rapid risks of accelerated erosion and non-point source pollution (NPSP). Agroforestry systems, conservation agriculture combined with crop residue mulch and intricate rotations along with INM, as well as water harvesting and recycling utilising micro-irrigation, are some technical choices that can increase the soil C budget, according to Lal et al. (2015). One of the most effective methods for regenerating ecosystems with degraded soils (eroded, salinized, and low fertility) and desertification is afforestation. The rate of soil carbon sequestration for secondary carbonates and SOC varies from 2 to 5 kg C/ha/yr and 100 to 1000 kg C/ha/yr, respectively.

i. Conservation tillage

Conservation tillage is an agricultural technique that leaves crop remains on the soil surface while minimizing soil disturbance during planting and cultivation. Because of its potential to increase carbon sequestration in agricultural systems, this approach has attracted a lot of attention. No-till has been proven to rapidly increase soil carbon, particularly at the soil surface, according to several studies (West and Post, 2002), and some more in-depth investigations have revealed a connection between this increase in carbon and increases in aggregation (Six et al., 2000). Conservation tillage techniques help agricultural areas accumulate soil organic carbon (SOC). Crop leftovers on the soil's surface serve as a source of organic matter that can eventually be absorbed into the soil and aid in SOC storage. Conservation tillage can boost SOC stocks by slowing the pace at which crop residues decompose and encouraging the production of stable soil aggregates (Blanco & Lal (2007). However, it is essential that soil aggregation be preserved in order to sustain advances in soil carbon. Baker et al. (2007) and Powlson et al. (2014) both note that a large number of investigations on no-till cultivation and conservation agriculture mainly indicate variations in carbon levels at the soil surface, while neglecting smaller depths where more intensive systems of tillage, like mouldboard plowing, might be actually relocating carbon. Syswerda et al. (2011) found that zero tillage farming continued to perform better than traditional farming. The promotion of carbon sequestration in agricultural systems is greatly aided by conservation tillage techniques. Conservation tillage helps to mitigate climate change by removing carbon dioxide from the atmosphere by decreasing soil erosion, increasing soil organic carbon, improving soil structure, and increasing crop yield. To create sustainable and climate-smart agricultural systems, farmers, decision-makers, and academics should continue to advocate for and adopt conservation tillage practices.

ii. Nutrient management

In agriculture, effective nutrient management techniques not only increase crop output, but they are also essential for carbon sequestration. Nitrogen (N), phosphorus (P), and potassium (K) are three nutrients that, when managed properly, can increase the amount of carbon that agricultural soils sequester. Compost, manure, or crop residues can be used as organic amendments to improve the soil's organic carbon (SOC) content and encourage carbon sequestration. Organic amendments boost microbial activity, increase carbon inputs into the soil, and raise soil fertility. Due to their high volumes of slowly decomposing organic matter, which serves as a long-term source of carbon for sequestration, these modifications help SOC build up (Six et al. 2002).

Chemical fertilisers, notably N_2O, are a source of GHG emissions. In addition to this, the manufacture of fertiliser and the transportation of it are linked to GHG emissions. When fertilisers are used wisely, crop yields and profitability increase. Additionally, the cultivated soils have added around 50 Pg of CO_2 to the atmosphere (Lal 2011) through the process of soil organic carbon (SOC) mineralization. Although studies show that nitrogen fertilization reduces soil microbial activity, their usage has significantly boosted agricultural productivity (Marschner et al. *2003,* Frey et al. *2014).* For sustainable soil fertility and crop output, balanced fertilizer usage must be ongoing (Verma et al. *2012).* Crop residues and nutrients, particularly N, aid in the sequestration of carbon by between 21.3 and 32.5% (Windeatt et al. *2014).*

iii. Cropping system and intensity

The amount of biomass produced, the incorporation of organic matter into the soil, and the overall carbon balance are all impacted by different cropping systems and management intensities. A 1500 Gt C pool is represented by soils. Variations in soil C stocks can result from any modification, change in land use, or change in land management (Bernoux *et al.* 2006). Intense cropping methods always result in SOM depletion, however applying crop residues, fertilizing with NPK in a balanced manner, and using organic amendments can raise carbon levels to 5-10 Mg ha^{-1} per year.

To sequester C in the form of SOM, which also provides stable soil structure, increased yield, and economic benefits, cropping intensity, and system optimization are necessary in agricultural systems (Drinkwater *et al.* 1998). The cropping system and intensity that is chosen have a big impact on how much carbon is stored in agricultural systems. To increase carbon sequestration, it is vital to use perennial cropping systems, agroforestry systems, cover crops, diversified crop rotations, reduced tillage techniques, and intercropping/relay crops.

iv. Mulching

Using organic or inorganic materials to cover the soil's surface is known as mulching in agronomy. This method has become well-known for its many advantages, including the possibility of enhancing carbon sequestration in agricultural systems. The mulch encourages carbon sequestration by introducing organic carbon to the soil as it breaks down (Six *et al.* 1999). Some mulch materials' slow rate of breakdown guarantees a long-term source of carbon for sequestration.

Mulch increases carbon concentration and SOM, and agricultural leftovers are frequently used as mulch to reduce CS and protect crops from cold stress. Mulch can improve the physical and chemical characteristics of agricultural soils while also increasing CS levels by 8–16 Mg ha^{-1} yr^{-1}. Utilising mulch raised the overall SOM from 1.26 to 1.50% (Kahlon et al. 2013). Mulch is essential for delivering nutrients since it participates in the C and N cycles and acts as a sink for carbon. It can considerably raise SOM and CS in the top 0–5 cm of soil.

Inorganic and organic mulching both contribute significantly to the promotion of carbon sequestration in agricultural systems. Enhancing organic matter input, lowering soil erosion, and enhancing soil microbial activity all help carbon sequestration when using organic mulch (Kahlon et al. 2013). By reducing weed development, controlling soil temperature, and preserving soil moisture, inorganic mulch indirectly promotes greater carbon sequestration. Farmers can enhance soil quality, boost carbon inputs into the soil, and mitigate climate change by implementing mulching practises.

v. Cover crops

In a similar vein, Camarotto et al., (2020) subsequent study looked into the effect of cover crops on carbon sequestration in European agroecosystems. They discovered that cover crops improved soil structure, increased nutrient availability, and decreased soil erosion in addition to enhancing SOC stocks. To achieve its goals of reducing climate change, the study emphasized the significance of cover crops as a sustainable management practise.

One common method for preserving and restoring SOM and soil productivity is the use of cover crops (Olson et al., 2014). An effective way to sequester C in agricultural systems is to grow cover crops and use advised management techniques. multiple reviews have reported that while cover crops may elevate the amount of SOC (Aguilera et al., 2013; Poeplau and Don, 2015), other research reveals no impact (Steele et al., 2012; Oliveira et al., 2016) and there have been decreases in organic carbon from the soil in the deeper soil horizons in some agricultural ecosystems (Tautges et al., 2019; Camarotto et al., 2020). Soil characteristics, climate, and management techniques all affect how effective cover cropping is at a given location (Peregrina et al., 2010). The importance of cycling through microbial communities for long-term carbon sequestration is also highlighted by a recent understanding of carbon and nutrient dynamics in soil ecosystems (Lehmann and Kleber, 2015; Kallenbach et al., 2016).

3. Conclusions

An important strategy for combating climate change and the rising quantities of atmospheric carbon dioxide is carbon sequestration. By capturing and storing carbon dioxide emissions, it provides a possible solution by lessening their environmental impact. There are many ways to address this worldwide issue using the many carbon sequestration techniques, including natural, technological, and biological approaches. Agronomic techniques, clay mineralogy, and organic additives all give intriguing opportunities for carbon sequestration in agriculture. While clay minerals and agronomic practices help to stabilize carbon and improve soil health, organic additions enrich soil organic matter. All terrestrial life is based on soil organic carbon, which is essential for maintaining both human health and the environment. It is the source of many ecosystem products and services produced by atmospheric processes. Gross soil C reservoir (including organic and inorganic) is the biggest terrestrial repository of C depending on land use and management, it can either be a source or sink of atmospheric CO2. It is essential to take a complete approach that incorporates multiple approaches and scales, adapted to circumstances, to fully reap the benefits of carbon sequestration.

Conflicts of interest

The authors declare no conflict of interest.

Author contribution

Authors S, OS, UPS, PKS, AS, VDR, TM, HER, KG write the original draft, and Authors S, OS, UPS, PKS, AS, VDR, TM, HER, KG edit and finalize the manuscript. All authors read and agree to the submission of the manuscript to the journal.

Acknowledgment

KG is supported by, under grant numbers 21AG-4C075 and FENW-2023-0008. AS is supported by the 23PostDoc-4D007 grant provided by the Science Committee of the Republic of Armenia. VDR and TM are supported by the Strategic Academic Leadership Program of Southern Federal University, known as "Priority 2030," and the Ministry of Science and Higher Education of the Russian Federation (grant number: FENW-2023-0008).

4. References

Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, Ecosystems and Environment, 168, 25–36. https://doi.org/10.1016/j.agee.2013.02.003

Angst, G., Kögel-Knabner, I., Kirfel, K., Hertel, D., & Mueller, C. W. (2016). Spatial distribution and chemical composition of soil organic matter fractions in rhizosphere and non-rhizosphere soil under European beech (Fagus sylvatica L.). Geoderma, 264:179–187. https://doi.org/10.1016/j.geoderma.2015.10.016

Baker, J. M., Ochsner, T. E., Venterea, R. T., & Griffis, T. J. (2007). Tillage and soil carbon sequestration—What do we really know? Agriculture, Ecosystems and Environment, 118(1–4), 1–5. https://doi.org/10.1016/j.agee.2006.05.014

Baldock, J. A. (2007). Composition and cycling of organic soil carbon in soil. In P. Marschner & Z. Rengel (Eds.), Nutrient cycling in terrestrial ecosystems, 1–35. Springer-Verlag. https://doi.org/10.1007/978-3-540-68027-7_1

Beare, M. H., Hu, S., Coleman, D. C., & Hendrix, P. F. (1997). Influences of mycelial fungi on soil aggregation and organic matter storage in conventional and no-tillage soils. Applied Soil Ecology, 5(3), 211–219. https://doi.org/10.1016/S0929-1393(96)00142-4

Bernoux, M., Cerri, C. C., Cerri, C. E. P., Neto, M. S., Metay, A., Perrin, A., Scopel, E., Razafimbelo, T., Blavet, D., Piccolo, Md. C., Pavei, M., & Milne, E. (2006). Cropping systems, carbon sequestration and erosion in Brazil, a review. Agronomy for Sustainable Development, 26(1), 1–8. https://doi.org/10.1051/agro:2005055

Blanco-Canqui, H., & Lal, R. (2007). Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. Soil and Tillage Research, 95(1–2), 240–254. https://doi.org/10.1016/j.still.2007.01.004

Camarotto, C., Piccoli, I., Dal Ferro, N. D., Polese, R., Chiarini, F., Furlan, L., & Morari, F. (2020). Have we reached the turning point? Looking for evidence of SOC increase under conservation agriculture and cover crop practices. European Journal of Soil Science, 71, 1050–1063. https://doi.org/10.1111/ejss.12953

Chatterjee, D., Datta, S. C., & Manjaiah, K. M. (2013). Clay carbon pools and their relationship with short-range order minerals: Avenues to mitigate climate change. Current Science, 105, 1404–1410.

Chen, H., Marhan, S., Billen, N., & Stahr, K. (2009). Soil organic-carbon and total nitrogen stocks as affected by different land uses in Baden-Württemberg (southwest Germany). Journal of Plant Nutrition and Soil Science, 172(1), 32–42. https://doi.org/10.1002/jpln.200700116

Chen, S., Xu, C., Yan, J., Zhang, X., Zhang, X., & Wang, D. (2016). The influence of the type of crop residue on soil organic carbon fractions: An 11-year field study of rice-based cropping systems in southeast China. Agriculture, Ecosystems and Environment, 223, 261–269. https://doi.org/10.1016/j.agee.2016.03.009

Christensen, B. T. (2001). Physical fractionation of soil and structural and functional complexity in organic matter turnover. European Journal of Soil Science, 52(3), 345–353. https://doi.org/10.1046/j.1365-2389.2001.00417.x

Clark, K. M., Boardman, D. L., Staples, J. S., Easterby, S., Reinbott, T. M., Kremer, R. J., Kitchen, N. R., & Veum, K. S. (2017). Crop yield and soil organic carbon in conventional and no-till organic systems on a claypan soil. Agronomy Journal, 109(2), 588–599.https://doi.org/10.2134/agronj2016.06.0367

Dal Ferro, N., Stevenson, B., Morari, F., & Müller, K. (2023). Long-term tillage and irrigation effects on aggregation and soil organic carbon stabilization mechanisms. Geoderma, 432, 116398. https://doi.org/10.1016/j.geoderma.2023.116398

Das SR, Nayak BK, Dey S, Sarkar S, Chatterjee D, Saha S, Sarkar D, Pradhan A, Saha S, Nayak AK. Potential soil organic carbon sequestration vis-a-vis methane emission in lowland rice agroecosystem. Environ Monit Assess. 2023, 195(9):1099. doi: 10.1007/s10661-023-11673-0.

Das, A., Purakayastha, T. J., Ahmed, N., Das, R., Biswas, S., Shivay, Y. S., Sehgal, V. K., Rani, K., Trivedi, A., Tigga, P., Sahoo, J., Chakraborty, R., & Sen, S. (2023). Influence of clay mineralogy on soil organic carbon stabilization under tropical climate, India. Journal of Soil Science and Plant Nutrition, 23(1), 1003–1018. https://doi.org/10.1007/s42729-022-01099-x

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing cropping system diversity balances productivity, profitability and environmental health. PLOS ONE, 7(10), e47149. https://doi.org/10.1371/journal.pone.0047149

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing cropping system diversity balances productivity, profitability and environmental health. PLOS ONE, 7(10), e47149. https://doi.org/10.1371/journal.pone.0047149

Denef, K., Six, J., Merckx, R., & Paustian, K. (2004). Carbon Sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Science Society of America Journal, 68(6), 1935–1944. https://doi.org/10.2136/sssaj2004.1935

Drinkwater, L. E., Wagoner, P., & Sarrantonio, M. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396(6708), 262–265. https://doi.org/10.1038/24376

Elbasiouny, H., & Elbehiry, F. (2019). Soil Carbon and Nitrogen Stocks and Fractions for Improving Soil Quality and Mitigating Climate Change. Egyptian Journal of Soil Science, 59(2), 131-144. doi: 10.21608/ejss.2019.9984.1251

El-Demerdash, S., Ali, A., & Sadik, A. (2019). Effect of Clay Minerals and Organic Matter Injection in El-Salhia Soil on Water Use Efficiency of Cucumber. Egyptian Journal of Soil Science, 59(4), 323-337. doi: 10.21608/ejss.2019.14756.1286

ElGhamry, A., Mosa, A., Elramady, H., GHAZI, D., elsherpiny, M., & helmy, A. (2024). Climate Change and the Possibility of Tea Production in the Egyptian Soils. Egyptian Journal of Soil Science, 64(2), 373-383. doi: 10.21608/ejss.2023.252241.1693

Elsherpiny, M. (2023). Role of compost, biochar and sugar alcohols in raising the maize tolerance to water deficit conditions. Egyptian Journal of Soil Science, 63(1), 67-81. doi: 10.21608/ejss.2022.178322.1556

Eshel, G., Fine, P., & Singer, M. J. (2007). Total soil carbon and water quality: An implication for carbon sequestration. Soil Science Society of America Journal, 71(2), 397–405. https://doi.org/10.2136/sssaj2006.0061

Fang, Y., Nazaries, L., Singh, B. K., & Singh, B. P. (2018). Microbial mechanisms of Carbon priming effects revealed during the interaction of crop residue and nutrient inputs in contrasting soils. Global Change Biology, 24(7), 2775–2790. https://doi.org/10.1111/gcb.14154

Farooqi, Z. U. R., Sabir, M., Zeeshan, N., Naveed, K., & Hussain, M. M. (2018). Enhancing Carbon Sequestration Using Organic Amendments and Agricultural Practices. Carbon Capture, Utilization and Sequestration, InTec. https://doi.org/10.5772/intechopen.79336

Frey, S. D., Ollinger, S., Nadelhoffer, K., Bowden, R., Brzostek, E., Burton, A., Caldwell, B. A., Crow, S., Goodale, C. L., Grandy, A. S., Finzi, A., Kramer, M. G., Lajtha, K., LeMoine, J., Martin, M., McDowell, W. H., Minocha, R., Sadowsky, J. J., Templer, P. H., & Wickings, K. (2014). Chronic nitrogen addition suppress decomposition and sequester soil carbon in temperate forests. Biogeochemistry, 121(2), 305–316. https://doi.org/10.1007/s10533-014-0004-0

Gómez, J. A. (2017). Sustainability using cover crops in Mediterranean tree crops, olives and vines – Challenges and current knowledge. Hungarian Geographical Bulletin, 66(1), 13–28. https://doi.org/10.15201/hungeobull.66.1.2

Gregorich, E. G., Drury, C. F., & Baldock, J. A. (2001). Changes in soil carbon under long-term maize in monoculture and legume-based rotation. Canadian

Journal of Soil Science, 81(1), 21–31. https://doi.org/10.4141/S00-041

Gross, A., & Glaser, B. (2021). Meta-analysis on how manure application changes soil organic carbon storage. Scientific Reports, 11(1), 1-13. https://doi.org/10.1038/s41598-021-82739-7

Guo, L., Shen, J., Li, B., Li, Q., Wang, C., Guan, Y., D'Acqui, L. P., Luo, Y., Tao, Q., Xu, Q., Li, H., Yang, J., & Tang, X. (2020). Impacts of agricultural land use change on soil aggregate stability and physical protection of organic C. Science of the Total Environment, 707, article 136049. https://doi.org/10.1016/j.scitotenv.2019.136049

HanWeng, Z., Van Zwieten, L., Singh, B. P., Tavakkoli, E., Joseph, S., Macdonald, L. M., Rose, T. J., Rose, M. T., Kimber, S. W. L., Morris, S., Cozzolino, D., Araujo, J. R., Archanjo, B. S., & Cowie, A. (2017). Biochar built soil carbon over a decade by stabilizing rhizodeposits. Nature Climate Change, 7(5), 371–376. https://doi.org/10.1038/nclimate3276

Hua, K., Wang, D., Guo, X., & Guo, Z. (2014). Carbon Sequestration Efficiency of Organic Amendments in a Long-Term Experiment on a Vertisol in Huang-Huai-Hai Plain, China. PLOS ONE, 9(9), e108594. https://doi.org/10.1371/journal.pone.0108594

Huang, X., Jia, Z., Jiao, X., Wang, J., & Huang, X. (2022). Long-term manure applications to increase carbon sequestration and macroaggregate-stabilized carbon. Soil Biology and Biochemistry, 174, 108827. https://doi.org/10.1016/j.soilbio.2022.108827

Hussein, M., Ali, M., Abbas, M., & Bassouny, M. (2022). Composting Animal and Plant Residues for Improving the Characteristics of a Clayey Soil and Enhancing the Productivity of Wheat Plant Grown Thereon. Egyptian Journal of Soil Science, 62(3), 195-208. doi: 10.21608/ejss.2022.154465.1524

Inbar, Y., Chen, Y., & Hadar, Y. (1990). Humic substances formed during the composting of organic matter. Soil Science Society of America Journal. Soil Science Society of America, 54(5), 1316–1323. https://doi.org/10.2136/sssaj1990.03615995005400050019x

IPCC. (2019). Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In.

IPCC. (2022). Summary for Policymakers. In Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (pp. 1-24). Cambridge: Cambridge University Press. doi:10.1017/9781009157940.001

Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. Environmental Research Letters, 12(5), 053001. https://doi.org/10.1088/1748-9326/aa67bd

Kahlon, M. S., Lal, R., & Ann-Varughese, M. (2013). Twenty-two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil and Tillage Research, 126, 151–158. https://doi.org/10.1016/j.still.2012.08.001

Kallenbach, C. M., Frey, S. D., & Grandy, A. S. (2016). Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications, 7, 13630. https://doi.org/10.1038/ncomms13630

Kane, D, and solutions, L.L.C. (2015). Carbon sequestration potential on agricultural lands: A review of current science and available practices. National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions. LLC, 1–35.

Kiem, R., & Kögel-Knabner, I. (2002). Refractory organic carbon in particle-size fractions of arable soils II: Organic carbon in relation to mineral surface area and iron oxides in fractions <6 μm. Organic Geochemistry, 33(12), 1699–1713. https://doi.org/10.1016/S0146-6380(02)00112-2

Kirkby, C.A., Richardson, A.E., Wade, L.J., Passioura, J.B., Batten, G.D., Blanchard, C., & Kirkegaard, J.A. (2014). Nutrient availability limits carbon sequestration in arable soils. Soil Biology and Biochemistry, 68, 402–409

Kleber, M., Eusterhues, K., Keiluweit, M., Mikutta, C., Mikutta, R., & Nico, P. S. (2015). Mineral–Organic Associations: Formation, Properties, and Relevance in Soil Environments. Advances in Agronomy, 130, 1–140. https://doi.org/10.1016/bs.agron.2014.10.005

Koga, N., and Tsuji, H. (2009). Increased soil organic carbon in the top 20 cm with straw incorporation. Journal of Soil Science and Plant Nutrition, 55(6), 777–782

Lal, R. (2011). Sequestering carbon in soils of agro-ecosystems. Food Policy, 36, S33–S39. https://doi.org/10.1016/j.foodpol.2010.12.001

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. Sustainability, 7(5), 5875–5895. https://doi.org/10.3390/su7055875

Lal, R. (2020b). Food security impacts of the "4 per thousand" initiative. Geoderma, 374. https://doi.org/10.1016/j.geoderma.2020.114427

Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. Current Opinion in Environmental Sustainability, 15, 79–86. https://doi.org/10.1016/j.cosust.2015.09.002

Lehmann, A., Zheng, W., & Rillig, M. C. (2017). Soil biota contributions to soil aggregation. Nature Ecology and Evolution, 1(12), 1828–1835. https://doi.org/10.1038/s41559-017-0344-y

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528(7580), 60–68. https://doi.org/10.1038/nature16069

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – A review. Mitigation and Adaptation Strategies for Global Change, 11(2), 403–427. https://doi.org/10.1007/s11027-005-9006-5

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. Soil Biology and Biochemistry, 43(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Li, C., Xiong, Y., Qu, Z., Xu, X., Huang, Q., & Huang, G. (2018). Impact of biochar addition on soil properties and water-fertilizer productivity of tomato in semi-arid region of Inner Mongolia, China. Geoderma, 331, 100–108. https://doi.org/10.1016/j.geoderma.2018.06.014

Li, S., Li, X., Zhu, W., Chen, J., Tian, X., & Shi, J. (2019). Does straw return strategy influence soil carbon sequestration and labile fractions? Agronomy Journal, 111(2), 897–906. https://doi.org/10.2134/agronj2018.08.0484

Li, Z., & Delvaux, B. (2019). Phytolith-rich biochar: A potential Si fertilizer in desilicated soils. GCB Bioenergy, 11(11), 1264–1282. https://doi.org/10.1111/gcbb.12635

Li, Z., Zhang, Q., Zhao, B., Cui, L., Zhang, H., & Qin, S. (2020). Biochar addition enhances soil organic carbon accumulation but not soil fertility: A 44-year field experiment in a paddy soil. Geoderma, 368, 114288.

Liang, C., Hao, X., Schoenau, J., Ma, B., Zhang, T., MacDonald, J. D., Chantigny, M., Dyck, M., Smith, W., Malhi, S. S., Thiagarajan, A., Lafond, J., & Angers, D. (2021). Manure-induced carbon retention measured from long-term field studies in Canada. Agriculture, Ecosystems & Environment, 321, 107619. https://doi.org/10.1016/j.agee.2021.107619

Liang, Q., Chen, H. Q., Gong, Y. S., Fan, M. S., Yang, H. F., Lal, R., & Kuzyakov, Y. (2012). Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a wheat-maize system in the North China Plain. Nutrient Cycling in Agroecosystems, 92(1), 21–33. https://doi.org/10.1007/s10705-011-9469-6

Liu, C., Wang, X., & Zhang, X. (2014). Shredded cotton stalks increased total and labile soil organic carbon. Soil and Tillage Research, 143, 1–7.

Loss, A., Pereira, M.G., Perin, A., Beutler, S.J., & Anjos, L.H.C. (2020). Characteristics of soil organic carbon fractions under different land uses in the Atlantic Forest biome. Journal of Soils and Sediments, 20, 1203–1212

Luo L, Wang J, Lv J, Liu Z, Sun T, Yang Y, Zhu YG. Carbon Sequestration Strategies in Soil Using Biochar: Advances, Challenges, and Opportunities. Environ Sci Technol. 2023, 57(31):11357-11372. doi: 10.1021/acs.est.3c02620.

Manlay, R. J., Feller, C., & Swift, M. (2007). Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agriculture, Ecosystems & Environment, 119(3-4), 217-233. https://doi.org/10.1016/j.agee.2006.07.011

Marschner, P., Kandeler, E., & Maschner, B. (2003). Structure and function of the soil microbial community in a long-term fertilization experiment. Soil Biology and Biochemistry, 35(3), 453–461. doi:10.1016/s0038-0717(02)00297-3

McLauchlan, K. K. (2006). Effects of soil texture on soil carbon and nitrogen dynamics after cessation of agriculture. Geoderma, 136(1–2), 289–299. https://doi.org/10.1016/j.geoderma.2006.03.053

Meier, E. A., & Thorburn, P. J. (2016). Long Term Sugarcane Crop Residue Retention Offers Limited Potential to Reduce Nitrogen Fertilizer Rates in Australian Wet Tropical Environments. Frontiers in Plant Science, 7. https://doi.org/10.3389/fpls.2016.01017

Nath, A. J., Lal, R., Sileshi, G. W., & Das, A. K. (2018). Managing India's small landholder farms for food security and achieving the "4 per thousand" target. Science of the Total Environment, 634, 1024–1033. https://doi.org/10.1016/j.scitotenv.2018.03.382

Nouri, M., Breuillin-Sessoms, F., Feller, U., Reinhardt, D., & Jansa, J. (2019). Shoot incorporation increased soil organic carbon by 1.5 Mg/ha in 5 months. Plant and Soil, 437(1–2), 1–11.

Oliveira, F. É. R., Oliveira, J. M., & Xavier, F. A. S. (2016). Changes in soil organic carbon fractions in response to cover crops in an orange orchard. Revista Brasileira de Ciência Do Solo, 40, e0150105. https://doi.org/10.1590/18069657rbcs20150105

Olson, K., Ebelhar, S. A., & Lang, J. M. (2014). Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open Journal of Soil Science, 04(8), 284–292. https://doi.org/10.4236/ojss.2014.48030

Padbhushan R, Sharma S, Kumar U, Rana D, Kohli A, Kaviraj M, Parmar B, Kumar R, Annapurna K, Sinha AK and Gupta VV (2021) Meta-Analysis Approach to Measure the Effect of Integrated Nutrient Management on Crop Performance, Microbial Activity, and Carbon Stocks in Indian Soils. Front. Environ. Sci. 9:724702. doi: 10.3389/fenvs.2021.724702

Pal, S., Pal, S., Chand, P., & Kandpal, A. (2023). Carbon sequestration potential of sustainable agricultural practices to mitigate climate change in Indian agriculture: A meta-analysis. Sustainable Production and Consumption, 35, 697–708. https://doi.org/10.1016/j.spc.2022.12.015

Pan, J, Wang, J, Zhuang, S (2024). Higher soil carbon and nitrogen sequestration in rice than non-rice soils following land reclamation. Soil and Tillage Research, 237, 105963. https://doi.org/10.1016/j.still.2023.105963.

Peregrina, F., Larrieta, C., Ibáñez, S., & García-Escudero, E. (2010). Labile organic matter, aggregates, and stratification ratios in a semiarid vineyard with cover crops. Soil Science Society of America Journal, 74(6), 2120–2130. https://doi.org/10.2136/sssaj2010.0081

Phillips CL, Wang R, Mattox C, Trammell TLE, Young J, Kowalewski A. High soil carbon sequestration rates persist several decades in turfgrass systems: A meta-analysis. Sci Total Environ. 2023; 858(Pt 3):159974. doi: 10.1016/j.scitotenv.2022.159974.

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops—A meta-analysis. Agriculture, Ecosystems and Environment, 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. Agriculture, Ecosystems & Environment, 200, 33-41. https://doi.org/10.1016/j.agee.2014.10.024

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B. A. S., Schumacher, J., & Gensior, A. (2011). Temporal dynamics of soil organic carbon after land-use change in the temperate zone carbon response functions as a model approach. Global Change Biology, 17(7), 2415–2427. https://doi.org/10.1111/j.1365-2486.2011.02408.x

Post, W. M., & Kwon, K. C. (2000). Soil Carbon sequestration and land-use change: Processes and potential. Global Change Biology, 6(3), 317–327. https://doi.org/10.1046/j.1365-2486.2000.00308.x

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. Nature Climate Change, 4(8), 678–683. https://doi.org/10.1038/nclimate2292

Reddy, K. R., Zhao, D., & Kakani, V. G. (2007). Haulms increased soil organic carbon by 1.2% over 4 years. Soil Science Society of America Journal, 71(6), 1895–1903.

RITZ, K., & YOUNG, I. (2004). Interactions between soil structure and fungi. Mycologist, 18(2):52-59. doi:10.1017/S0269915X04002010

Roß, C., Baumecker, M., Ellmer, F., & Kautz, T. (2022). Organic Manure Increases Carbon Sequestration Far beyond the “4 per 1000 Initiative” Goal on a Sandy Soil in the Thyrow Long-Term Field Experiment DIV.2. Agriculture, 12(2), 170. https://doi.org/10.3390/agriculture12020170

Saikanth , D. R. K., Singh , B. V., Rai , A. K., Kumar , U. S., Surender, Yadav , B., & Singh , O. (2023). Biochar Implementation in Rice Paddies for Addressing Greenhouse Gas Emissions and Nutrient Loss: A Review. International Journal of Plant & Soil Science, 35(18), 610–623.

Salehi, A., Fallah, S., & Sourki, A. A. (2017). Organic and inorganic fertilizer effect on soil CO2 flux, microbial biomass, and growth of Nigella sativa L. International Agrophysics, 31(1), 103–116. https://doi.org/10.1515/intag-2016-0032

Schiedung, M., Tregurtha, C. S., Beare, M. H., Thomas, S. M., & Don, A. (2019). Deep soil flipping increases carbon stocks of New Zealand grasslands. Global Change Biology, 25(7), 2296–2309. https://doi.org/10.1111/gcb.14588

Sherrod, L. A., Peterson, G. A., Westfall, D. G., & Ahuja, L. R. (2003). Cropping intensity enhances soil organic carbon and nitrogen in a no-till agroecosystem. Soil Science Society of America Journal, 67(5), 1533–1543. https://doi.org/10.2136/sssaj2003.1533

Shukla, P. R., Skea, J., Buendia, E., Calvo, M.-D., V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J., Portugal, V., . . . Malley, J. (Eds.). Summary for policymakers.

Singh, O., Singh, S., Singh, V.K., Singh, A. (2023). Biochar: An Organic Amendment for Sustainable Soil Health. In: Baskar, C., Ramakrishna, S., Daniela La Rosa, A. (eds) Encyclopedia of Green Materials. Springer, Singapore. https://doi.org/10.1007/978-981-16-4921-9_265-1

Six, J., & Paustian, K. (2014). Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biology and Biochemistry, 68, A4–A9. https://doi.org/10.1016/j.soilbio.2013.06.014

Six, J., Bossuyt, H., De Gryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research, 79(1), 7–31.

Six, J., Conant, R.T., Paul, E.A. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil, 241, 155–176. https://doi.org/10.1023/A:1016125726789

Six, J., Elliott, E. T., & Paustian, K. (1999). Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Science Society of America Journal, 63(5), 1350–1358. https://doi.org/10.2136/sssaj1999.6351350x

Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biology and Biochemistry, 32(14), 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Speratti, A., & Whalen, J. K. (2007). Soil carbon, nitrogen, and phosphorus as affected by cover crop and compost in an organic vegetable cropping system. Nutrient Cycling in Agroecosystems, 79(3), 187–198. https://doi.org/10.1007/s10705-007-9117-z

Steele, M. K., Coale, F. J., & Hill, R. L. (2012). Winter annual cover crop impacts on no-till soil physical properties and organic matter. Soil Science Society of America Journal, 76(6), 2164–2173. https://doi.org/10.2136/sssaj2012.0008

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. (2007). Soil carbon saturation: Concept, evidence and evaluation. Biogeochemistry, 86(1), 19–31. https://doi.org/10.1007/s10533-007-9140-0

Syswerda, S. P., Corbin, A. T., Mokma, D. L., Kravchenko, A. N., & Robertson, G. P. (2011). Agricultural Management and Soil Carbon Storage in Surface vs. Deep Layers. Soil Science Society of America Journal, 75(1), 92-101. https://doi.org/10.2136/sssaj2009.0414

Tautges, N. E., Chiartas, J. L., Gaudin, A. C. M., Herrera, I., & Scow, K. M. (2019). Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology, 25(11), 3753-3766. https://doi.org/10.1111/gcb.14762

Tisdall, J. M., and Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. Journal of Soil Science, 33(2), 141-163.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., & Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. Agricultural Systems, 134, 6–16. https://doi.org/10.1016/j.agsy.2014.05.009

Verhoeven, E. M., Jansen, B., & Lehmann, J. (2019). Biochar reduces the nitrogen footprint of cropping systems. Agriculture, Ecosystems and Environment, 278, 41.

Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., & Six, J. (2017). Toward a better assessment of biochar–nitrous oxide mitigation potential at the field scale. Journal of Environmental Quality, 46(2), 237–246. https://doi.org/10.2134/jeq2016.10.0396

Verma, G., Sharma, R. P., Sharma, S. P., Subehia, S. K., & Shambhavi, S. (2012). Changes in soil fertility status of maize–wheat system due to long-term use of chemical fertilizers and amendments in an alfisol. Plant, Soil and Environment, 58(12), 529–533. https://doi.org/10.17221/133/2012-PSE

Wallace, P. (2007). Compost use in agriculture consolidated report phase 2. Grant Scape and the Applied Research Forum. London. Routledge, Taylor and Francis Group.

Wang C, Kuzyakov Y. Rhizosphere engineering for soil carbon sequestration. Trends Plant Sci. 2023, S1360-1385(23)00323-0. doi: 10.1016/j.tplants.2023.09.015.

Wang S, Xu L, Adhikari K, He N. Soil carbon sequestration potential of cultivated lands and its controlling factors in China. Sci Total Environ. 2023, 905:167292. doi: 10.1016/j.scitotenv.2023.167292.

Wang, D., Fonte, S. J., Parikh, S. J., Six, J., & Scow, K. M. (2017a). Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. Geoderma, 303, 110–117. https://doi.org/10.1016/j.geoderma.2017.05.027

Wang, Y., Hu, N., Ge, T., Kuzyakov, Y., Wang, Z., Li, Z., Tang, Z., Chen, Y., Wu, C., & Lou, Y. (2017b). Soil aggregation regulates distributions of carbon, microbial community and enzyme activities after 23-year manure amendment. Applied Soil Ecology, 111, 65–72. https://doi.org/10.1016/j.apsoil.2016.11.015

Wang, Y., Hu, N., Xu, M., Li, Z., Lou, Y., Chen, Y., Wu, C., & Wang, Z. L. (2015). 23-year manure and fertilizer application increases soil organic carbon sequestration of a rice–barley cropping system. Biology and Fertility of Soils, 51(5), 583–591. https://doi.org/10.1007/s00374-015-1007-2

Wei, X., Shao, M., Gale, W., & Li, L. (2014). Global pattern of soil carbon losses due to the conversion of forests to agricultural land. Scientific Reports, 4(4062), 4062. https://doi.org/10.1038/srep04062

Wen, Y., Liu, W., Deng, W., He, X., & Yu, G. (2019). Impact of agricultural fertilization practices on organo-mineral associations in four long-term field experiments: Implications for soil C sequestration. Science of the Total Environment, 651(1), 591–600. https://doi.org/10.1016/j.scitotenv.2018.09.233

West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Science Society of America Journal, 66(6), 1930–1946. https://doi.org/10.2136/sssaj2002.1930

Windeatt, J. H., Ross, A. B., Williams, P. T., Forster, P. M., Nahil, M. A., & Singh, S. (2014). Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment. Journal of Environmental Management, 146, 189–197. https://doi.org/10.1016/j.jenvman.2014.08.003

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. Nature Communications, 1, 56. https://doi.org/10.1038/ncomms1053

Wu, D., Lin, J. C., Duarte, H. F., Yadav, V., Parazoo, N. C., Oda, T., & Kort, E. A. (2021). A model for urban biogenic CO2 fluxes: Solar-Induced Fluorescence for Modeling Urban biogenic Fluxes (SMUrF v1). Geoscientific Model Development, 14, 3633–3661. https://doi.org/10.5194/gmd-14-3633-2021.

Wu, L., Wei, C., Zhang, S., Wang, Y., Kuzyakov, Y., & Ding, X. (2019). MgO-modified biochar increases phosphate retention and rice yields in saline-alkaline soil. Journal of Cleaner Production, 235, 901–909. https://doi.org/10.1016/j.jclepro.2019.07.043.

Wu, L., Zhang, S., Ma, R., Chen, M., Wei, W., & Ding, X. (2021). Carbon sequestration under different organic amendments in saline-alkaline soils. CATENA, 196, 104882. https://doi.org/10.1016/j.catena.2020.104882.

Yang, X., Meng, J., Lan, Y., Chen, W., Yang, T., Yuan, J., Liu, S., & Han, J. (2017). Effects of maize stover and its biochar on soil CO2 emissions and labile organic carbon fractions in Northeast China. Agriculture, Ecosystems and Environment, 240, 24–31. https://doi.org/10.1016/j.agee.2017.02.001.

Yeasmin S, Assaduzzaman, Kabir MS, Anwar MP, Islam AKMM, Hoque TS. (2022). Influence of Organic Amendments on Soil Carbon Sequestration Potential of Paddy Soils under Two Irrigation Regimes. Sustainability, 14(19), 12369. https://doi.org/10.3390/su141912369.

Zhang T, Tang Y, Li H, Hu W, Cheng J, Lee X. A bibliometric review of biochar for soil carbon sequestration and mitigation from 2001 to 2020. Ecotoxicol Environ Saf. 2023, 264:115438. doi: 10.1016/j.ecoenv.2023.115438.

Zhang W, Wan Q, Zhu G, Xu Y. Distribution of soil organic carbon and carbon sequestration potential of different geomorphic units in Shiyang river basin, China. Environ Geochem Health. 2023; 45(6):4071-4086. doi: 10.1007/s10653-022-01472-w.

Zhu S, Sainju UM, Zhang S, Tan G, Wen M, Dou Y, Yang R, Chen J, Zhao F, Wang J. Cover cropping promotes soil carbon sequestration by enhancing microaggregate-protected and mineral-associated carbon. Sci Total Environ. 2024, 908:168330. doi: 10.1016/j.scitotenv.2023.168330.

Zhu, L., Hu, N., Zhang, Z., Xu, J., Tao, B., & Meng, Y. (2015). Short-term responses of soil organic carbon and carbon pool management index to different annual straw return rates in a rice-wheat cropping system. CATENA, 135, 283–289. https://doi.org/10.1016/j.catena.2015.08.008.