Carbon Sequestration In Vegetable Crops

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Abstract

Carbon sequestration in vegetable crops represents a crucial strategy for mitigating climate change by capturing and storing atmospheric carbon dioxide (CO_2). Vegetable crops, through their growth processes, absorb CO_2 during photosynthesis, converting it into organic matter that can be retained in plant tissues and the soil. This process not only helps reduce the amount of CO_2 in the atmosphere but also improves soil health and fertility, creating a more sustainable agricultural system. Various practices enhance carbon sequestration in vegetable cropping systems. These include optimizing planting densities, selecting cover crops and implementing no-till or reduced-till farming methods. Cover crops, such as legumes and grasses, can enhance soil organic matter and increase microbial activity, which in turn improves soil structure and carbon storage. Additionally, practices like compost application and crop rotation contribute to the stabilization of organic carbon in the soil. Different vegetable crops exhibit varying capacities for carbon sequestration based on their growth habits, root systems and overall biomass production. For instance, deep-rooted crops may contribute more to soil carbon storage by increasing the depth and stability of carbon in the soil profile. Moreover, integrating vegetable crops with other sustainable agricultural practices, such as agroforestry and organic farming, can further enhance carbon sequestration potential. Understanding and maximizing the carbon sequestration potential of vegetable crops involves considering both agronomic and environmental factors. Research and field studies are essential for developing guidelines and strategies tailored to specific crops and regional conditions. By adopting and promoting effective carbon sequestration practices in vegetable farming, we can contribute to climate change mitigation efforts, enhance soil health, and support the sustainability of global food systems.

1. Introduction

Climate change is an ongoing natural phenomenon that has been part of Earth's history. While the rate of climate change can vary from decades to millennia according to the, the current warming trend is of particular concern because over 95 % of its likelihood is attributed to human activities since the mid-twentieth century. Although certain levels of greenhouse gases (GHGs) are necessary for maintaining a livable atmosphere, the current rate of warming is occurring approximately ten times faster than the average rate during ice age recovery periods. The primary driver of this global warming is the increasing concentration of GHGs in the atmosphere due to human activities. Carbon dioxide (CO_2) is the most abundant and long-lasting GHG in the atmosphere. Climate models indicate that the earth's average surface temperature has risen by about 1°C since the late nineteenth century, largely due to higher concentrations of atmospheric CO_2. Almost half of the warming effect globally is attributed to CO_2 alone among all GHGs. CO_2 enters the atmosphere through both natural processes like soil respiration and volcanic eruptions, as well as human activities such as fossil fuel combustion, deforestation and changes in land use. Since the industrial revolution, human-induced CO_2 emissions have increased approximately threefold, with the industrial sector playing a significant role in elevating atmospheric CO_2 levels from 280 parts per million (ppm) to 400 ppm over the past 150 years.

The essence of sustainability in olericulture is rooted in the principle of meeting present needs without compromising the ability of future generations to meet their own. Sustainable agriculture embodies an ecosystem-centered approach that prioritizes three fundamental objectives: maintaining a healthy environment, ensuring economic viability upholding social and economic equity. By adopting sustainable agricultural practices, biodiversity within ecosystems can be preserved and nurtured. This approach discourages the use of resource-intensive inputs such as harmful pesticides, synthetic fertilizers, genetically modified seeds, other practices that degrade soil, water and natural resources. Instead, it promotes the use of resource-conserving techniques like crop rotation, conservation tillage, and pasture-based livestock management to optimize the utilization of non-renewable resources. Sustainable agriculture integrates methods aimed at achieving long-term plant and animal production. Harmful practices like land degradation, excessive soil tillage leading to erosion, and inadequate drainage causing salinization pose significant environmental risks. The goal of sustainable agriculture is to enhance soil health while minimizing reliance on non-renewable resources, thus ensuring a sustainable agricultural future (Sanaullah *et al*., 2019).

There is a growing demand for technically feasible and economically viable strategies aimed at reducing global atmospheric CO_2 levels while simultaneously enhancing soil health and quality. Carbon sequestration emerges as a promising approach in this endeavor, aiming to mitigate the concentration of CO_2 in the atmosphere to counteract global climate change while also fostering improved soil conditions for enhanced plant growth. Broadly defined, carbon sequestration encompasses both natural and intentional processes that involve the removal of CO_2 from the atmosphere or its redirection from emission sources to be stored in carbon sinks such as oceans and terrestrial environments (including vegetation, soils, and sediments).

Meeting the food demands of a rapidly growing population without expanding agricultural land and causing environmental harm poses a significant challenge for the agriculture sector (Stevenson *et al*. 2013). Carbon sequestration emerges as a remarkable approach to ensure food security, agricultural sustainability and reduce global atmospheric CO_2 levels. Agricultural management practices such as minimum- or zero-tillage systems, the use of synthetic fertilizers combined with organic amendments, crop rotation, and incorporation of crop residues have the potential to increase soil carbon storage and thereby enhance agricultural sustainability (Six *et al*. 2002).

2. Ways to achieve carbon sequestration

2.1. Geological carbon sequestration

Geological carbon sequestration, also known as geological carbon capture and storage (CCS), is a process that involves capturing carbon dioxide (CO_2) emissions from industrial sources, such as power plants and factories and injecting them deep underground into geological formations for long-term storage. This method is gaining attention as a promising strategy to mitigate greenhouse gas emissions and combat climate change. The process of geological carbon sequestration typically involves three main steps: capture, transportation and storage. During the capture phase, CO_2 is captured from industrial sources, usually through processes like pre-combustion capture, post-combustion capture or oxy-fuel combustion. Once captured, the CO_2 is compressed into a dense fluid for transportation to suitable storage sites. Transportation of the compressed CO_2 often occurs via pipelines or ships to reach suitable geological formations for storage. These formations typically include deep saline aquifers, depleted oil and gas reservoirs, and unmendable coal seams. These formations offer large underground spaces with impermeable cap rocks that can securely trap the injected CO_2 over long periods. Once at the storage site, the CO_2 is injected deep underground into the selected geological formation. Once injected, the CO_2 is stored in the porous spaces of the rock formation, where it undergoes processes such as dissolution in saline water, mineralization or trapping in structural or residual forms. Monitoring and verification techniques are employed to ensure the integrity and safety of the storage site and to confirm that the injected CO_2 remains securely stored underground.

2.2. Ocean sequestration

Ocean sequestration is a method of carbon capture and storage that involves the absorption and storage of carbon dioxide (CO_2) from the atmosphere into the oceans. The process takes advantage of the ocean's natural ability to absorb CO_2, primarily through physical and chemical processes. One mechanism of ocean sequestration is the dissolution of CO_2 into seawater, where it reacts with water molecules to form carbonic acid. This acid can then undergo further reactions to produce bicarbonate ions and carbonate ions, effectively storing the carbon in the ocean for long periods. Another method involves enhancing the growth of phytoplankton, tiny marine organisms that photosynthesize and absorb CO_2 from the atmosphere during their

life cycle. When these organisms die, they sink to the ocean floor, effectively sequestering carbon in the deep ocean sediments. While ocean sequestration has the potential to mitigate climate change by reducing the amount of CO_2 in the atmosphere, it also raises concerns about its potential impacts on marine ecosystems and ocean chemistry. Additionally, the long-term effectiveness and feasibility of ocean sequestration as a climate change mitigation strategy remain subjects of ongoing research and debate.

2.3. Terrestrial sequestration

Terrestrial carbon sequestration refers to the process by which carbon dioxide (CO_2) is removed from the atmosphere and stored in terrestrial ecosystems such as forests, grasslands, wetlands and soils. This natural process is critical for mitigating climate change by reducing the concentration of greenhouse gases in the atmosphere. Forests play a crucial role in terrestrial carbon sequestration through the process of photosynthesis, where trees and plants absorb CO_2 from the air and convert it into organic carbon through the synthesis of sugars and other compounds. This carbon is stored in the biomass of trees and vegetation. Additionally, soils act as a significant carbon sink, storing large amounts of carbon in the form of organic matter derived from decomposed plant material.

Various land management practices can enhance terrestrial carbon sequestration. Afforestation and reforestation initiatives involve planting trees on land that was previously devoid of forests or had been deforested, thus increasing carbon storage in biomass. Conservation tillage, cover cropping and agroforestry techniques help increase carbon sequestration in agricultural soils by reducing soil disturbance and increasing organic matter content.

While terrestrial carbon sequestration has the potential to mitigate climate change and provide additional benefits such as biodiversity conservation and soil fertility improvement, it also faces challenges such as deforestation, land degradation and land use conflicts. Effective policies and incentives are necessary to promote sustainable land management practices and maximize the carbon sequestration potential of terrestrial ecosystems.

3.0 Carbon storage in earth’s ecosystem

Carbon storage in Earth's ecosystems is a key process that helps regulate the global carbon cycle. Forests, soils, oceans and wetlands act as major carbon sinks, absorbing and storing carbon dioxide (CO_2) from the atmosphere. Forests sequester carbon in trees and vegetation, while soils store organic carbon.. Human activities like deforestation and fossil fuel use disrupt this balance, leading to increased atmospheric CO_2 and global warming. Protecting these ecosystems is crucial for mitigating climate change.

Table 1. Different earth ecosystem carbon storage

Different land system	In vegetation (t C/ha)	In soil (t C/ha)
Boreal forest	64	344
Temperate forest	57	96
Temperate grassland	7	236
Tropical forest	**120**	123
Desert and semideserts	2	42
Tundru	6	127
Wet land	43	**643**
Crop land (Including vegetable)	2	80

4.0 Factors affecting carbon sequestration in soil

4.1. Climatic factors.

4.1.1 Precipitation

Maintaining soil moisture within the optimal range, spanning from field capacity to the permanent wilting point, fosters favorable conditions for soil carbon sequestration. This range promotes robust vegetation growth, facilitating increased input of plant residues into the soil. Any deviation from this optimal moisture level can hinder soil carbon sequestration. Fluctuations in soil moisture levels outside the optimum range may lead to decreased plant input, thereby impeding carbon storage in the soil. When soil moisture is limited, falling below the permanent wilting point, it diminishes vegetation growth, consequently exerting a negative impact on soil carbon sequestration.

4.1.2 Temperature

Processes involved in soil carbon cycling exhibit a high sensitivity to temperature, where even minor increases can trigger significant releases of carbon from the soil (Classen *et al*., 2015). Elevated temperatures promote the decomposition of organic matter by accelerating the metabolic rates of soil microorganisms. Changes in temperature also impact the activity, functioning, and community structure of soil microbes (Bradford *et al*., 2008). The heightened microbial activity resulting from warmer conditions could potentially exacerbate global warming through positive feedback loops. However, this effect may be mitigated under lower soil moisture conditions.

4.1.3 Elevated CO_2

Increased atmospheric CO_2 levels have both direct and indirect effects on soil quality and plant growth. It is widely acknowledged that elevated CO_2 levels enhance plant growth and photosynthesis, especially in

nutrient-rich soils (Curtis and Wang, 1998). This augmentation may lead to greater carbon flux to plant roots through the release of labile sugars, proteins, and organic acids into the rhizosphere. The increased deposition of organic matter by roots can indirectly influence soil processes by stimulating plant growth and facilitating the return of atmospheric CO_2 to the soil through the biological breakdown of litter, roots, and rhizodeposits. Changes in the rates and composition of these rhizodeposits under elevated CO_2 levels can significantly impact the composition, biomass, and activity of rhizosphere microorganisms. Elevated atmospheric CO_2 levels may also induce modifications in the entire ecosystem, including alterations in the microbe-soil-plant root system, potentially affecting soil moisture content, root growth, and rhizodeposition.

4.2. Edaphic factors

4.2.1. Soil texture

Clay particles exhibit a negative charge, and clayey soils typically possess a higher proportion of micro-pores compared to macro-pores. Consequently, organic matter (OM) tends to be more shielded within the structure of clayey soils relative to coarse-textured soils. This heightened protection of organic matter within clay particles amplifies the potential for soil carbon sequestration in these soil types. The physical safeguarding and stabilization of soil organic carbon (SOC) in mineral soils are predominantly linked to their cation exchange capacity (CEC) or clay content.

4.2.2. Soil structure

Soil structure plays a vital role in imparting biological stability to soil organic matter (SOM) by influencing factors such as water and oxygen availability, providing physical protection from microbial communities, and influencing soil aggregation dynamics. Less-structured soils tend to have a higher prevalence of free particulate organic matter (f-POM), leading to increased organic matter degradation. Conversely, well-structured soils predominantly harbor occluded particulate organic matter (o-POM), resulting in reduced SOM decomposition. Consequently, well-structured soils positively contribute to soil carbon sequestration, whereas poorly-structured soils may hinder carbon storage in the soil.

4.2.3. Soil porosity

Soil porosity, defined by a continuum of pores ranging from micro-pores (<0.1 mm) to macro-pores (>20 mm), influences the processes of organic matter (OM) decomposition and mineralization. Adequate water and oxygen availability within these pores optimize these processes. Clayey soils, with a greater proportion of micro-pores, play a significant role in soil carbon sequestration by potentially providing protection against soil microorganisms. The transformation of clayey soils into sandy soils, characterized by a higher proportion of macro-pores, can alter pore size distribution, potentially enhancing the mineralization of soil organic carbon (SOC) due to increased air-filled porosity.

4.2.4. Soil compaction

Soil compaction refers to the compression of soil particles, resulting in decreased pore spaces for air and water. This compression can lead to a reduction in soil organic carbon (SOC) by inhibiting the addition of plant litter and the accumulation of carbon in surface soil layers. The potential for soil carbon sequestration is significantly diminished in compacted soils, primarily due to an increase in soil bulk density and a decrease in plant inputs to the soil.

4.2.5. Soil mineralogy

Soil carbon storage capacity is significantly influenced by the mineralogical characteristics of the soil. Clay minerals play a crucial role in adsorbing and protecting organic carbon, with their effectiveness determined by mineralogy, surface charge distribution and the presence of Fe and Al oxides precipitated on clay minerals. Organic substances interact with clay minerals through two main mechanisms: the formation of complexes through physical and chemical retention, and stabilization through the sorption of organic particles onto clay surfaces (involving cation and anion exchange, hydrogen bonding, and polyvalent cation bridging). Additionally, organic matter can be physically stabilized by penetrating into the interlayer spaces of expanding clay minerals.

4.2.6. Soil microbial community composition

Soil microbes play a dominant role in the carbon and nutrient cycling within ecosystems, with their activities shaped by both abiotic and biotic factors such as temperature, moisture levels and the quantity and quality of plant residue inputs. Changes in precipitation and soil moisture content can influence the ratio of fungi to bacteria. A diverse array of soil microbes—including fungi, bacteria, actinomycetes and microalgae—significantly contribute to the decomposition of soil organic matter, nutrient cycling and various chemical transformations within the soil.

5. Plant characteristics for high carbon sequestration

Plants that are well-suited for carbon sequestration typically have high rates of photosynthesis, extensive root systems, and produce large amounts of biomass. Here are some plant characteristics to look for:

5.1. Fast growth: Plants that grow quickly, such as bamboo or certain grass species like Miscanthus, can sequester carbon rapidly through photosynthesis, converting atmospheric carbon dioxide into organic carbon in plant tissues.

5.2. Deep root systems: Plants with deep and extensive root systems, such as certain trees like oak, pine, or poplar, can help store carbon below ground as organic matter. These deep roots can penerate into the soil, increasing its organic carbon content and improving soil structure.

5.3. Perennial growth: Perennial plants, which live for multiple years, have the advantage of continuously sequestering carbon over their lifespan. This includes perennial grasses, shrubs, and trees, which maintain vegetation cover and contribute to long-term carbon storage in ecosystems.

5.4. Nitrogen fixation: Some plants, particularly legumes like clover, alfalfa or soybeans including leguminous vegetable like snapbean, cluster bean, dolichos bean etc., have the ability to fix atmospheric nitrogen through symbiotic relationships with nitrogen-fixing bacteria. This not only enhances soil fertility but also increases carbon sequestration through increased biomass production.

5.5. Drought tolerance: Plants that are adapted to dry conditions, such as certain succulents or desert shrubs, can still sequester carbon even in arid environments. Their ability to survive with limited water means they can continue photosynthesizing and storing carbon, albeit at a slower rate.

5.6.High lignin content: Plants with high lignin content, such as certain grasses and woody plants, tend to decompose more slowly, allowing for longer-term carbon storage in soil organic matter.

6. Methods for estimating carbon pool

Estimating the carbon pool within ecosystems is essential for understanding the role of natural and managed environments in the global carbon cycle. Accurate measurement of carbon stocks helps in assessing the effectiveness of carbon sequestration efforts and in monitoring changes due to land use or climate change. Various methods are employed to estimate carbon pools, each tailored to different components of the ecosystem, such as biomass, soil and dead organic matter. These methods range from direct field measurements to remote sensing technologies and modeling approaches, providing comprehensive insights into the carbon dynamics of an ecosystem.

Table 2. Different methods to estimate carbon pool

Above ground biomass	Below ground biomass	Litter and deadwood	Soil carbon
Harvest method Remote sensing Modelling Plot method	Root extraction and weight measurement Root to shoot ratio Biomass equation	Litter trap Stock measurement	Sample and laboratory estimation Diffuse reflectance spectroscopy Modeling

7. Strategies for carbon sequestration in soil

7.1. Conservation tillage

7.2. Crop residue

7.3. Crop rotation and diversification

7.4. Organic farming

7.5. Cover crops

7.6. Perennial crops

7.7. Biochar application

7.1. Conservation tillage

Conservation tillage, involving minimal or zero soil disturbance, aims to reduce the extensive working of soil. The transition from permanent vegetation cover to annual crops, such as in forests and grasslands, has led to a significant loss of initial carbon stocks. Studies suggest approximately a 20 % loss, equivalent to around 1500 grams per square meter of soil, within the top 30 centimeters. Moreover, after 20 years of cultivation, an estimated 30 % of the initial carbon is lost, with the majority occurring within the first five years. This loss primarily stems from intensive soil manipulation, which exposes the protected organic matter, leading to increased aeration and subsequent microbial decomposition. To counteract this carbon loss, conservation tillage methods like reduced tillage (RT) or no-till (NT) are advocated to promote carbon sequestration. Minimising tillage with grafted vegetables like in brinjal, can increase life of crop by 2-3 years.

7.2. Crop residue

Soil organic carbon (SOC) primarily originates from plant-derived carbon that undergoes microbial processing, and its stability is influenced by various soil, climate and environmental factors. Both the quantity and quality of carbon inputs play crucial roles in determining SOC stocks. Extractive agricultural practices, which involve the removal of aboveground biomass, are common in agriculture, particularly in developing countries. These practices contribute to the depletion of SOC in global soils. Reversing these practices by leaving or incorporating a significant portion of aboveground biomass in the field can help restore and increase SOC stocks. By increasing crop residue inputs and minimizing carbon losses from soils, SOC levels can be augmented until a new equilibrium is reached. However, the effectiveness of increasing SOC through plant residue inputs depends on several factors, including residue quality, tillage methods, climate, soil type, and overall management practices. Of these factors, tillage and other management practices can be controlled to some extent on a farm to promote SOC sequestration.

Red pepper was grown to evaluate influence of carbonized crop residue on soil carbon storage by Lee *et al*., 2017. The present study confirmed that the respiration rate can be reduced by carbonization of residue biomass and putting it in the soil and that the respiration rate and soil temperature were positively correlated. Based on the results, it was determined that approximately 1.2 t C/ha were sequestered in the soil in the first

year and 3.0 t C/ha were stored in the following year. Therefore, approximately 1.5 t C/ha/year are expected to be stocked in the soil, making it possible to develop farmlands into carbon pools.

7.3. Perennial crop

Perennial crops have longer growing seasons and continuous root growth compared to annual crops. This prolonged root activity contributes to the accumulation of organic matter in the soil, as roots exude carbon-rich compounds into the rhizosphere, providing a food source for soil microbes and promoting soil carbon sequestration. It often require minimal soil disturbance, especially if managed with conservation tillage or no-till practices. This reduces the exposure of soil organic matter to decomposition, thus helping to retain carbon in the soil. It typically have deeper root systems and greater biomass accumulation compared to annual crops. This results in more organic matter being added to the soil over time, leading to increased carbon sequestration potential. It can improve soil structure and stability through the formation of deeper root networks and the incorporation of organic matter into the soil. Improved soil structure facilitates better water infiltration and retention, which can further enhance carbon sequestration by promoting microbial activity and organic matter decomposition. Perennial crops with their longer growing periods and continuous ground cover, help reduce soil erosion by protecting the soil surface from water and wind erosion. This helps to preserve soil organic matter and prevent carbon loss from erosion.

The cultivation of drumstick variety Dhanraj released from UASD, Dharwad and Bhagya released from UAHS, Bagalkot, PKM-1 from TNAU and other IIHR varieties can be used for carbon sequestration effectively.

The total of 462 numbers of 10 trees species present in selected area of north Maharashtra university Jalgaon. The above ground and below ground organic carbon (tonns/tree) and total organic carbon of each species were calculated. *Moringa olifera* species was found to be dominant sequestrated 15.775 tons of carbon and having 14 trees followed by *Azadirachta indica* 12.272 tons. The species *Eucalyptus citriodora* has lowest carbon sequestration potential that is 1.814 tones (Suryawanshi *et al*., 2014).

7.4. Organic amendments

Organic amendments involve incorporating animal manure (such as from livestock, pigs or poultry), biosolids and sludge into agricultural soils. Long-term and consistent use of animal manure as an amendment has been demonstrated to significantly enhance soil fertility compared to control sites that either receive mineral fertilizers or none at all. Organic amendments can increase soil organic carbon (SOC) concentration and stocks through two main pathways. Direct contribution that is Manure-C undergoes microbial processing, leading to a direct addition of organic carbon to the soil. Enhanced organic carbon input from plants that is manure application enhances plant productivity, resulting in higher inputs of plant-derived carbon into the soil.

This suggests that organic amendments may be more effective in boosting SOC stocks compared to plant-derived inputs like straw application or residue incorporation. The proportion of applied carbon that becomes SOC is quantified as the manure/straw/residue-C retention coefficient (%), where a higher retention coefficient indicates a greater percentage of applied carbon becoming part of the SOC.

Chinese cabbage (*Brassica chinensis* L.) is grown under organic and conventional method to study the soil organic carbon (SOC), soil labile carbon (SLC), soil organic carbon storage (SOCS) and the yield by Sardiana *et al*. (2014). The SOC, SLC and SOCS were significantly ($P< 0.05$) higher under organic than the conventional counterpart after five years application of organic system.

Xu *et al*., 2024 carried out a 6-year field experiment, following four fertilization treatments at consistent nitrogen levels: solely mineral fertilizer; and organic fertilizers replacing 20 %, 50 %, and 100 % of mineral nitrogen fertilizer. They assessed carbon dioxide emissions derived from various sources, soil properties, nutrient availability, enzyme activity. Organic fertilizers provided a large amount of labile substrate, diminishing the microbial requirement for enzyme production in SOC decomposition. Notably, 50 % organic substitution consistently outperformed others, consistently yielding 1.17 to 1.29 times more than alternative treatments. Furthermore, this approach exhibited the lowest cumulative priming effect, which declined by 26.9 % to 44.8 %, attributed to enhanced soil organic carbon stability. Therefore, a 50 % organic substitution effectively balances carbon sequestration and the priming effect, contributing to sustainable vegetable production.

The research exploring the changes in soil organic carbon and the microbial community mediated by soil aggregates, or their impacts on soil productivity was studied by Tong *et al*., 2023. This study investigated the properties of soil aggregates, including the levels of organic carbon fractions, microbial community, and enzyme activity with the three aggregate classes: microaggregates (<0.25 mm), small macroaggregates (2–0.25 mm) and large macroaggregates (>2 mm) under conventional cultivation (CC), integrated cultivation (IC), and organic cultivation (OC) in greenhouses. The results showed that OC and IC promoted the formation of small macroaggregates and enhanced aggregate stability compared to CC. Organic cultivation significantly increased enzyme activity in all three particle-size aggregates and increased the relative abundance of bacteria in microaggregates as well as the relative abundance of fungi in small macroaggregates. In conclusion, long-term organic cultivation in greenhouses improves soil structure, increase soil fertility and vegetable yield, and has a positive impact on the environment. Organic cultivation increases soil fertility and contributes to maintaining ecological balance and protecting the environment in greenhouses.

7.5. Crop rotation

Crop rotation is a farming practice where different crops are grown successively on a piece of land to maintain soil health, control pests, weeds and diseases. Unlike natural ecosystems, which exhibit above ground biodiversity across spatial scales, cropping systems primarily rely on temporal diversity achieved through crop

rotation. Prairie grasslands demonstrate that increased biodiversity enhances primary productivity, resource efficiency, nutrient availability and ecosystem stability. While the weed and disease suppression benefits of crop rotation have long been recognized, recent studies highlight additional belowground advantages such as improved nutrient cycling, soil organic carbon content, microbial biomass and soil structure. These benefits are further accentuated when combined with no-till practices (Nunes *et al*. 2018).

Legumes offer a promising alternative to mineral nitrogen fertilization, with studies showing their inclusion in cropping sequences can reduce carbon and nitrogen losses from various agricultural ecosystems. Additionally, the incorporation of legumes leads to a net accumulation of soil organic matter (SOM), as higher rates of biomass addition and turnover facilitate the incorporation of soil organic carbon (SOC). Emphasizing minimal mineral nitrogen application emerges as a highly recommended strategy for climate-smart soil management (Paustian *et al*. 2016).

Effects of cropping pattern on soil carbon sequestration and their aggregate stability in long term agricultural fields was investigated by Salam *et al*., 2021. Results showed that Soil organic carbon (SOC) value was improved for vegetable field from 4.06 to 9.11 g/kg and carbon stock (20.14 mg C ha /year) as well as soil carbon sequestration rate was the highest in vegetable field (1.12 mg C ha/year).

From 2002 to 2006, field experiments were conducted at the soil and water management research institute in Thanjavur, Tamil Nadu, India, evaluating ten different cropping systems across the *Kharif* (June to September), *rabi* (October to January), and summer (February to April) seasons. The focus was on assessing the productivity of these systems and their impact on soil organic carbon content and soil available nitrogen. The incorporation of legumes into the cropping systems notably enhanced the soil's organic carbon levels. Specifically, cropping systems involving rice (*Oryza sativa*) followed by blackgram (*Vigna mungo*), onion (*Allium cepa*), groundnut (*Arachis hypogea*) followed by blackgram, and rice followed by greengram (*Vigna radiata*) showed improvements in soil organic carbon content and soil available nitrogen status. Furthermore, the inclusion of blackgram and greengram in rice-based cropping systems resulted in increased yields for the subsequent rice crop (Porpavai *et al*., 2011)

Parmer and Thakur. 2017 conducted a nine-year (2004 to 2013) long-term fertilization experiment involving three management practices (organic, inorganic and integrated) and four cropping systems: tomato – cauliflower - green pea, french bean – french bean - cauliflower, cauliflower – cauliflower - green pea and maize - french bean - garlic. Their findings reveal that surface soil bulk density decreased (1.40 g cm^{-3}), while it increased in the sub-surface (1.42 g cm^{-3}). The topsoil layer exhibited the highest organic carbon content (1.07%) along with increased soil bacteria (8.6 x 106 cfu g^{-1}), fungi (4.5 x 106 cfu g^{-1}), and phosphatase enzyme activity (9.3 µ p-nitrophenol g^{-1}). Moreover, the organic inputs led to enhanced soil organic carbon stock (22.5 t/ha/yr), carbon sequestration (17.0 t/ha/yr), carbon sequestration rate (2.5 t/ha/yr), and various carbon fractions (C fract1: 0.48 t/ha/yr, C fract2: 0.25 t/ha/yr, C fract3: 0.14 t/ha/yr, C fract4: 0.21 t/ha/yr).

Although cropping systems had less impact on soil bulk density, they significantly influenced other soil variables in the topsoil layer, albeit not in the sub-layer. Among the cropping systems, cauliflower – cauliflower – green pea exhibited the most substantial improvements in organic carbon (0.88%), total soil organic carbon stock (18.9 t/ha/yr), carbon sequestration (11.7 t/ha/yr), carbon sequestration rate (2.9 t/ha/yr), and various carbon fractions (C fract1: 0.35 t/ha/yr, C fract2: 0.22 t/ha/yr, C fract3: 0.12 t/ha/yr , C fract4: 0.17 t/ha/yr), along with increased soil bacteria (8.7 x 106 cfu g^{-1}), fungi (3.2 x 106 cfu g^{-1}), and phosphatase enzyme activity (7.6 µ p-nitrophenol g^{-1}).

In a field trial conducted in Karnataka, India, spanning from 1993-94 to 1995-96, NP and N fertilizers at varying rates (50 % and 100 %) were applied to successive wheat crops (cv. Bijaga Yellow) following the harvest of potatoes (cv. Kufri Chandramukhi). The growth and yield attributes of these crops notably surpassed those of the control group. Interestingly, applying 50 % of the recommended nitrogen (N) produced a yield of 1967 kg/ha, which was statistically similar to yields obtained with 100 % NP (1997 kg/ha), 100 % N (2007 kg/ha), and 50 % NP (1917 kg/ha). These yields were all superior to those of the control. Observations showed soil enrichment with organic carbon, available nitrogen (N), phosphorus (P), and potassium (K) after the potato crop. While there was a subsequent depletion in organic carbon and soil nutrient content after the wheat harvest, these nutrients were replenished following the next potato crop. Importantly, the overall net nutrient and organic carbon content were higher compared to the initial soil fertility status, indicating the positive impact of the cropping system and fertilizer application on soil health and productivity over the trial period (Ramesh and Prabhakar, 2000).

The primary aim of this research was to evaluate carbon stocks and carbon dioxide sequestration across different land use systems within the same area with twenty-year-old cultivation. Soil samples were gathered from various depths (0-15 cm, 15-30 cm, 30-50 cm and 50-100 cm) in mango orchards, cashew orchards, rose gardens, vegetable plots, and medicinal and aromatic cropping systems. The findings revealed that carbon sequestration was notably higher in mango orchards followed by cashew orchards compared to annual crops such as rose, medicinal, aromatic plants and vegetables. Perennial crops significantly contributed to carbon dioxide sequestration compared to annual crops. Perennial horticultural crops were observed to enhance soil organic carbon (SOC) and carbon dioxide storage while reducing carbon emissions into the atmosphere, thereby aiding in the mitigation of global warming (Bhavya *et al*., 2018)

7.6. Cover crops

Cover crops play a pivotal role in mitigating climate change by sequestering carbon from the atmosphere and storing it in the soil. These crops, typically planted between main crops or during fallow periods, offer a multitude of benefits, including soil erosion prevention, nutrient cycling, and improvement of soil health. However, one of their most significant contributions lies in their ability to enhance carbon sequestration in agricultural soils. When cover crops are grown, they undergo photosynthesis, a process where

they absorb carbon dioxide from the air and convert it into organic matter. This organic matter is then deposited into the soil through the decomposition of cover crop residues and root exudates. As a result, carbon is stored in the soil in the form of soil organic carbon (SOC). The amount of carbon sequestered depends on various factors, including cover crop species, biomass production, and soil management practices. Cover crops, with their extensive root systems, enhance soil structure and stability, promoting the formation of aggregates that protect organic carbon from decomposition. Additionally, cover crop residues act as a physical barrier, reducing soil erosion and preventing carbon loss through runoff. Furthermore, cover crops contribute to increased microbial activity in the soil. Soil microbes decompose cover crop residues, releasing carbon as microbial biomass, which can then be stabilized as SOC. This enhanced microbial activity also facilitates nutrient cycling and improves overall soil health.

In Dharwad, Karnataka, India, a field experiment was conducted during the *kharif* season of 1997. The experiment featured four cover crops (*Stylosanthes hamata*, lucerne, Centrosema, and Calopogonium), two row proportions (1:1 and 1:2 of chilli to cover crop), and two cutting intervals of cover crops (30 and 45 days), with sole chilli serving as the control. The soil initially contained 179.92 kg/ha of available nitrogen, 31.02 kg/ha of available phosphorus and 385.10 kg/ha of available potassium. Cover crops were sown in the second fortnight of July with a spacing of 90 × 60 cm. Weed dry weight was monitored at 45, 90 and 135 days after transplanting (DAT). Incorporating cover crops resulted in reduced weed dry weight at all growth stages compared to the control, with Calopogonium exhibiting the lowest weed dry weight (0.87 g/sq) at 45 DAT. Additionally, a row proportion of 1:2 and a 45-day cutting interval provided effective weed control. Lucerne cover crop demonstrated superior performance in terms of dry biomass production (11.038 t/ha) and nitrogen addition (269.315 kg/ha). Soil organic carbon content was highest with lucerne cover crop (0.740 %) compared to other cover crops. Conversely, sole chilli without cover crop displayed higher weed dry weight at all stages and lower soil organic carbon levels after chilli harvest. The nitrogen uptake by chilli was highest (66.69 kg/ha) when grown with *S. hamata* cover crop. A row proportion of 1:1 (60.84 kg/ha) and a 30-day cutting interval (60.85 kg/ha) resulted in increased nitrogen uptake. Notably, sole chilli recorded higher nitrogen uptake (63.27 kg/ha) compared to chilli grown with cover crops (excluding *S. hamata*). A similar trend was observed with phosphorus uptake by chilli (Basavagouda *et al*., 2000)

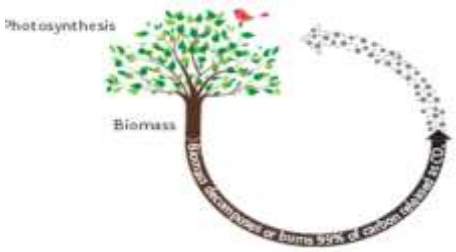
7.7. Use biochar

This thorough review delves into the utilization of biochar, a sustainable solid material obtained from biomass pyrolysis and rich in carbon, as a promising approach for soil carbon sequestration. It provides an in-depth analysis of the current understanding of biochar's application in this area. The review commences by examining the properties of biochar and the methods used for its production, emphasizing its resilient nature as a potential stable carbon repository. It further investigates the impact of different feedstocks and pyrolysis conditions on the diverse physicochemical properties of biochar and its potential for sequestering carbon in

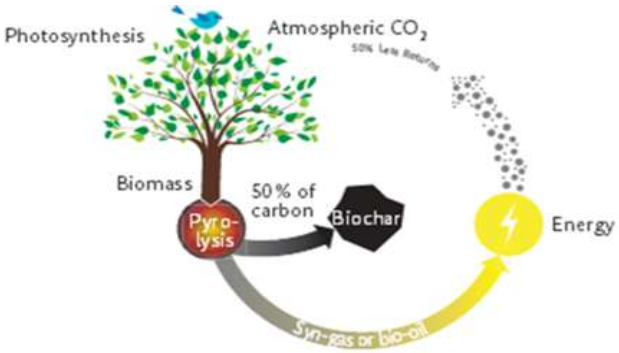
soil. The mechanisms by which biochar enhances soil carbon sequestration are thoroughly discussed, including its role as a physical barrier against carbon loss and its capacity to foster stable soil aggregates and influence soil microorganisms. The review also addresses challenges and constraints, such as variations in biochar characteristics and optimal application rates, while proposing strategies for maximizing the efficacy of biochar through amendments.

Furthermore, the review underscores the significance of long-term field studies, standardized protocols, and economic evaluations to bolster the widespread adoption of biochar for soil carbon sequestration and its potential in mitigating climate change. By providing a comprehensive overview of biochar's role in soil carbon sequestration and addressing pertinent challenges and opportunities, this review serves as a valuable resource for researchers, policymakers, and practitioners in the field of environmental sustainability.

8. Comparision of carbon cycle and biochar cycle



Most carbon returns to atmosphere.Green plants use solar energy to remove CO_2 from the atmosphere via photosynthesis and store it as chemical energy in biomass. when biomass decomposes or burns, this process is reversed and nearly all CO_2 returned to the atmosphere.



Up to 50 % of carbon stays in the soil

Pyrolysis destroys the structure of the biomass. One half remains in the created char. If the char is buries in the soil as biochar, most of the carbon stays there and is sequestered as biochar.

Kongsager *et al*., 2013

9. Pragmatic impacts of soil organic carbon on soil health .

9.1. Physical impact

9.1.1. Aggregate stability

9.1.2. Pore size distribution

9.1.3. High water retention

9.1.4. Root proliferation

9.1.5. Physical protection against erosion

9.2. Chemical impact

9.2.1. Higher organic matter status

9.2.2. Higher cation exchange capacity (CEC)

9.3.3. High buffering capacity of soil

9.3.4 Higher soil fertility

9.3. Biological impact

9.3.1. Proliferated microbial activity

9.3.2. Increased nutrients cycling

9.3.3. Higher nutrient availability

9.3.4. Increased enzyme activity

10. Effect on cropping pattern and intensity

Maysoon *et al*. (2010) investigated the influence of cropping intensity and fallowing on carbon sequestration rates. Various crops, including winter wheat, corn, pearl millet, dry pea and fallows, were incorporated into different cropping intensities. Their findings revealed that crop rotations with higher intensity significantly increased soil carbon sequestration compared to those with fallows. The inclusion of dry pea, a legume, in crop rotation had a negligible impact on carbon sequestration when compared to rotations involving summer fallows. Higher cropping intensity led to the formation of macro-aggregates, particularly in no-till soil, while less intensive rotations exhibited minimal aggregate development. The increased formation of macro-aggregates under higher cropping intensity facilitated the preservation of particulate organic matter and soil organic matter, especially in the most intensive crop rotations. Consequently, the most intensive crop rotations demonstrated practical benefits for soil carbon storage, as well as its protection and stabilization within soil aggregates.

11. Effect on crop yield and productivity

Both restoring and enhancing the soil carbon pool are essential for mitigating atmospheric greenhouse gas levels and improving agronomic productivity and food security. Boosting carbon sequestration is critical for enhancing soil quality and health, as well as maximizing the effectiveness of agricultural inputs such as

agro-chemicals and water. The beneficial effects of valuable farm inputs, including superior crop varieties, advanced agro-chemicals and enhanced management techniques, can only be fully realized by improving soil carbon levels.

12. Effect on global environment

Soil organic matter (SOM) holds significant potential for mitigating climate change by potentially reducing greenhouse gas (GHG) emissions into the atmosphere. Numerous studies indicate that many agricultural soils, even those partially degraded. It can play a substantial role in mitigating the rise in global CO_2 levels. Soil organic matter is increasingly recognized as a critical soil component, capable of acting as both a source and a sink for atmospheric GHGs, contributing to global warming (Lal, 2002). Globally, soils contain approximately twice as much carbon (C) as the atmosphere and vegetation combined.The rate of carbon sequestration varies widely, ranging from 100 to 1000 kg/ha/year for soil organic C and 5–15 kg/ha/year for soil inorganic C, depending on factors such as soil properties, climate, land-use changes, and cropping practices (Lal, 2009). Climate change prediction models suggest that an annual reduction of 3.5–4 gigatons (Gt) in CO_2 emissions could potentially limit temperature increases to 1.5–2 °C by 2050. However, achieving this annual reduction in atmospheric CO_2 concentration requires enhancing carbon storage in the deeper layers of soils (Minasny *et al*., 2017).

13. Conclusion

Carbon sequestration presents a promising strategy for reducing atmospheric CO_2 levels, thereby mitigating global climate change and enhancing soil health to support better plant growth and ensure food security. Among climatic factors, soil organic matter (SOM) decomposition is more sensitive to rising temperatures than changes in precipitation and elevated CO_2 levels. Soil texture primarily influences the accumulation of soil organic carbon (SOC). The impact of agricultural practices on carbon sequestration varies significantly among different soil types. Soil physical and biological characteristics play crucial roles in determining the amount of SOC in response to different agricultural practices over short time periods. Adopting conservation tillage or no-till practices can mitigate carbon loss caused by intensive tillage, with additional benefits for increasing soil organic matter content achievable through proper cropping sequences and patterns. Incorporating legumes into cropping systems presents a viable option for enhancing SOC storage in the soil. The strategy of carbon sequestration offers a valuable tool for advancing the objectives of sustainable agriculture, as it not only enhances the physical, chemical, and biological health of soil but also mitigates the presence of pollutants in the soil.

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