

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; 8(12): 159-168
www.biochemjournal.com
Received: 12-09-2024
Accepted: 20-10-2024

Souvik Ghosh
Ph.D. Research Scholar in Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal, India

Divya D
Ph.D. Research Scholar, Department of Soil Science, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences Iruvakkki, Shimoga, Karnataka, India

Ankita Nath
Ph.D. Division of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology, Wadura, Jammu & Kashmir, India

Virendra Singh Yadav
Ph.D., Department of Agronomy, Research Scholar, Sardar Vallabhbhai Patel University of Agriculture & Technology, Modipuram, Meerut, Uttar Pradesh, India

Sukhdham Singh
Ph.D. Agronomy 1st year, Sardar Vallabhbhai Patel University of Agriculture and Technology Modipuram Meerut, Uttar Pradesh, India

Syed Andleebajan
Division of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology, Sopore, Jammu & Kashmir, India

Smriti Hansda
Assistant Professor (SWCE), College of Agriculture, Bhanuaniapatna, Odisha University of Agriculture and Technology, Odisha, India

Anil Kumar
Assistant Professor, Department of Agronomy, Eklavya University Damoh, Madhya Pradesh, India

Corresponding Author:
Anil Kumar
Assistant Professor, Department of Agronomy, Eklavya University Damoh, Madhya Pradesh, India

Carbon sequestration in agricultural soils: Strategies for climate change mitigation-A Review

Souvik Ghosh, Divya D, Ankita Nath, Virendra Singh Yadav, Sukhdham Singh, Syed Andleebajan, Smriti Hansda and Anil Kumar

DOI: <https://doi.org/10.33545/26174693.2024.v8.i12c.3087>

Abstract

Agricultural soils play a central role in climate change mitigation by sequestering carbon. Carbon sequestration captures atmospheric carbon dioxide (CO₂) and stores it in soil organic matter. This paper discusses the potential of agricultural practices to improve soil carbon storage, their implications on climate change mitigation, and some of the challenges associated with implementing them. Strategies include conservation tillage, agroforestry, bio-char application, cover cropping, and improved nutrient management. The paper concludes with a call for integrated approaches, policy support, and research to optimize these practices for global sustainability.

Keywords: Carbon sequestration, agricultural soils, climate change, soil organic matter, mitigation strategies

1. Introduction

Agricultural soils act as carbon sources and sinks. They constitute an essential part of the global carbon cycle (Liu *et al.* 2022) ^[69]. Intensification of agriculture over a century coupled with deforestation, misuse of land and soils, and mismanagement has reduced SOC to alarming rates (Zuazo *et al.* 2011) ^[123]. These reduced SOC have been reported to increase atmospheric GHG emission while declining soil fertility, water retaining ability, and biodiversity (Lal R, 2015) ^[64]. Global Research estimates that soils lost, between 50% to 70% of the original carbon content from since the advent of modern agriculture mainly through degradation processes such as erosion, decomposition, and mineralization (Abbas *et al.* 2020) ^[1].

The loss of carbon from soils to the atmosphere as CO₂ aggravates global warming, thereby creating a feedback loop that further destabilizes ecosystems (Lal R, 2013) ^[57]. However, this same process offers an opportunity (Sanaullah *et al.* 2022) ^[97] by reversing these trends and enhancing SOC levels, agricultural soils can act as significant carbon sinks, capturing and storing atmospheric CO₂.

Lal *et al.* 2007 ^[62] emphasize the many benefits of terrestrial carbon sequestration, such as compensating for human-induced emissions, reducing the net increase in atmospheric CO₂ levels, and enhancing soil and water quality along with their ecosystem functions and services. Other advantages include decreasing nutrient losses from ecosystems, reducing erosion risks, improving habitats, enhancing water retention, rehabilitating degraded soils, and increasing the efficiency of land use. Such diverse benefits have led to strong interest in the development of clear frameworks, experimental methods, laboratory procedures, and techniques for measuring carbon sequestration through plant materials, residues, and other organic substances integrated into soil organic matter (Batjes, 1998) ^[7].

Understanding the global carbon balance of ecosystems is indispensable for ascertaining the magnitude of carbon reservoirs and to set new directions for management of ecosystems (Lal, 2004) ^[55]. This review aims at summarizing knowledge on soil roles, most importantly its important role in carbon sequestration that mitigates climatic effects. Being the largest carbon reservoir on Earth, the soil plays an important role in the carbon cycle, and thus constitutes a prime resource in controlling climate change.

It thus explains the significance of soil as it delves into the critical factors that impact its carbon sequestration potential (Smith P, 2004) ^[105].

These factors range from environmental conditions such as climate, geographical features including topography, the original composition of the soil known as parent material, variety of organisms in the soil, and intrinsic properties of the soil such as texture, structure, and organic matter content. To arrive at a balanced view, the review takes a two-step approach. First, the paper provides a bibliometric analysis of seven key terms related to the topic for an objective view of the current research trends. A detailed literature review is further offered to provide deeper insights into the role of soil in carbon sequestration and its potential for climate change mitigation.

1.1 Importance of Carbon Sequestration in Agriculture

Agricultural soils can potentially sequester as much as 0.8-1.2 gigatons of CO₂ per year (Shahzad *et al.* 2022) [97]. This means not only the offsetting of GHG emissions but also the co-benefits that include better soil structure, higher nutrient availability, and improved water retention. Additionally, carbon sequestration in soils supports SDGs related to food security, reduction of poverty, and ecological resilience (Bhattacharya *et al.* 2016) [8].

1.2 Causes of Soil Carbon Loss

Deforestation and land-use change, such as converting forests into agricultural lands, release stored carbon from vegetation and soil, thereby significantly reducing the levels of soil organic carbon (SOC) (Hendrickson, 2023). Conventional tillage practices expose organic matter to oxygen, accelerating its decomposition and releasing CO₂ into the atmosphere (Bossio *et al.*, 2020) [12]. Monocropping and long periods of bare soil reduce carbon inputs and increase susceptibility to erosion, while chemical-intensive farming, with excessive use of synthetic fertilizers and pesticides, can limit soil microbial diversity, severely impacting carbon stabilization processes.

1.3 Opportunity in Agricultural Practice

Regenerative agriculture represents a potential route for rebuilding SOC under the condition that agricultural productivity is either maintained or improved (Khangura *et al.* 2023) [50]. Practices such as conservation tillage, cover cropping, crop rotation, agroforestry, and bio-char application may all capture carbon in soils (Toensmeier E, 2016) [112]. Such practices serve to store carbon while addressing important problems such as soil degradation, desertification, and declining crop yields.

Despite the potential, there are several barriers to the widespread adoption of these practices, including lack of awareness, economic constraints, and the need for supportive policies and incentives (Lal R, 2004) [55]. Addressing these barriers requires a multi-stakeholder approach, encompassing farmers, policymakers, researchers, and private sector participants (Wreford *et al.* 2017) [119].

The underlying science of soil carbon sequestration, agricultural management that enhances it, and related consequences for climate change mitigation and sustainable agriculture (Sommer R, & Bossio D, 2014) [108]. It gives greater depth to the underlying ideas of such practices towards making an agricultural system resurfaced with resilience by ensuring carbon neutrality at global level (Follett RF, 2001) [32].

2. Role of soil in carbon cycle

Soils play an essential role in the global carbon cycle. It serves both as a massive source of carbon and sink (Dioxide

AC, 1985) [21]. While soils store more carbon in the atmosphere and on Earth's land than atmospheric or terrestrial vegetation, soil is critical to regulate atmospheric carbon dioxide (CO₂) concentrations (Ebouel *et al.* 2024) [27]. Carbon in soil mainly exists in two forms (1) SOC (Soil Organic Carbon) and (2) SIC (Soil Inorganic Carbon). Both are unique sources for carbon cycling (Tan *et al.* 2014) [110]. Soils, through SOC and SIC, play a critical role in the equilibrium of the global carbon cycle (Lal R, 2019) [60]. Sustainable management of soil resources is essential to increasing carbon sequestration and reducing greenhouse gas emissions for food security (Lal R, *et al.* 2021) [63]. It means understanding and optimizing soil carbon dynamics as a natural system with which humanity can more effectively fight climate change (Minasny *et al.* 2017) [76].

2.1 Soil Organic Carbon (SOC)

SOC is a dynamic and biologically active pool of soil carbon derived from the decomposition of organic materials such as plant residues, animal waste, and microbial biomass (Bhattacharya *et al.* 2016) [8]. SOC sequestration is very important in climate mitigation through the removal of CO₂ from the atmosphere and its storage in stable soil organic matter (Lorenz & Lal, 2014) [70]. Moreover, SOC is vital for maintaining soil health and contributes to fertility, water retention, and structural stability, thus enhancing agricultural productivity (Lal, 2016) [59].

A balance of inputs and outputs in the form of SOC level influences the dynamics, the input is carbon addition; and the output is SOC loss due to decomposition and erosion (Doetterl *et al.* 2016) [24].

The carbon inputs to the soil are from plant residues, root exudates, and organic amendments such as compost or manure, which are rich in carbon (Guo LB, Gifford RM 2002) [38]. Through decomposition, microbial activity breaks down this organic matter, releasing CO₂ into the atmosphere or transforming it into more stable forms (Paustian *et al.*, 2016) [83]. Stabilization mechanisms include chemical stabilization, where SOC forms stable complexes with minerals that slow its decomposition, physical protection (Wiesmeier *et al.* 2019) [118], where organic matter is safeguarded within soil aggregates to limit microbial access, and biochemical resistance, where compounds like lignin resist microbial decomposition (Lehmann & Joseph, 2024) [66].

2.1.1 Agricultural Practices and SOC

Human agriculture has significantly impacted soil organic carbon storage and dynamics (Jobbágy & Jackson, 2000) [47]. Among the positive impacts include the adoption of conservation tillage, cover cropping, crop rotations that increase the levels of SOC, and also the inclusion of organic amendments such as bio-char that enhances carbon sequestration (Schlesinger & Amundson, 2019) [99]. However, such activities that include intensive tillage make organic matter decompose at greater rates and lose carbon with overgrazing and forest clearing depleting stocks of SOC (Fuss *et al.*, 2014) [35].

2.2 Soil Inorganic Carbon (SIC)

SIC is primarily a stable and geochemically significant form of soil carbon (Ferdush J, (2022) [31], composed primarily of carbonates such as calcium carbonate (CaCO₃), especially in arid and semi-arid regions that contribute to the long-term

storage of carbon (Ebouel *et al.* 2024) ^[27]. Being less dynamic than SOC, SIC interacts with the soil process through (Zomer *et al.* 2017) ^[121].

The formation of carbonates occurs when CO₂ reacts with calcium or magnesium, resulting in the precipitation of stable carbonates. The dissolution and reprecipitation of these carbonates are influenced by changes in soil pH, temperature, and moisture, altering the carbonate pool. Soils play a crucial role in carbon-climate dynamics (Grimm *et al.* 2008) ^[37]. Carbon sequestration occurs when soils with significant levels of SOC absorb and retain carbon, helping to lower atmospheric CO₂ and mitigate climate change (Lal, 2004) ^[55]. Conversely, degraded soils release stored carbon into the atmosphere, becoming carbon sources.

Sustainable land management practices are suggested for soils to play a significant role in the carbon budget. Agroforestry practice, which involves the incorporation of trees into agricultural landscapes, enhances carbon inputs and SOC storage (Zomer *et al.*, 2016) ^[122]. Reduced tillage helps minimize soil disturbance, therefore reducing SOC losses (Dimassi *et al.* 2013) ^[20]. Organic farming contributes to SOC by adding organic matter to the soil (Nelson & Sommers 1996) ^[81]. Further, recovering degraded lands enhances vegetation cover, thus increasing carbon storage.

3. Carbon Sequestration in Agricultural Soils

Carbon sequestration in agricultural soils is the implementation of practices that increase the storage of SOC while enhancing sustainable farming (Lal R, 2004) ^[55]. These strategies will also enhance soil health, along with the improvement of ecosystem services and climate change mitigation (Singh *et al.* 2018) ^[102].

Carbon sequestration strategies in agricultural soils, though challenging (Powlson *et al.* 2011) ^[88], represent the enormous potential for climate change mitigation and sustainable agriculture (Freibauer *et al.* 2004) ^[34]. Technological advancement, favorable government incentives, and well-informed farmers may still facilitate the large-scale introduction of these practices (Lal R, Negassa W, Lorenz K, 2015) ^[64]. Indeed, by integrating these strategies into agriculture, we would both improve soil health and resilience against climate change (Tiefenbacher *et al.* 2021) ^[111].

3.1 Conservation Tillage

Conservation tillage minimizes or eliminates mechanical plowing, reducing soil disturbance (Carter MR, 2017) ^[14]. No-till, strip-till, and reduced-till systems all maintain soil structure, retain organic matter, and decrease carbon loss (Blanco & Lal 2023) ^[9].

Conservation tillage works by leaving crop residues on the soil surface, forming a protective cover that reduces erosion and promotes the accumulation of organic carbon (Hussain *et al.*, 2021) ^[42]. This practice offers several benefits, including improved soil structure by preventing compaction, enhancing porosity, and encouraging root penetration. It also improves water retention by reducing runoff and increasing infiltration, thereby conserving soil moisture (Balesdent *et al.* 2000) ^[6]. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and tillage* Additionally, conservation tillage fosters microbial growth by creating a stable soil environment that supports beneficial microbes, which help stabilize SOC (Hamza *et al.* 2005) ^[39]. However, it has limitations, such as increased

reliance on herbicides for weed control, which can have environmental implications, and the need for specific machinery like no-till seed drills, leading to higher initial investments for farmers.

3.2 Agroforestry

Agroforestry is the integration of trees and shrubs into farming systems combining agricultural and forestry practices for sustainable land use (Raj *et al.* 2019) ^[91]. Trees sequester carbon in their biomass and improve soil organic carbon through litter and root inputs (Swarup *et al.* 2019) ^[109].

Agroforestry combines woody perennials with crops or livestock to create a layered system that mimics natural ecosystems, enhancing carbon storage and biodiversity (Malézieux, 2012) ^[72]. This practice offers several benefits, including increased biodiversity by creating habitats for diverse species and enhancing ecological balance. It also adds income streams through products like timber, fruits, nuts, or fodder, diversifying farm income. Additionally, agroforestry supports ecosystem stability by preventing soil erosion, regulating water flow, and buffering against extreme weather conditions (Post & Kwon 2000) ^[85]. However, it faces challenges such as land-use competition, where trees reduce space available for other crops, and the long-term nature of investment, as trees require years to grow before providing returns.

3.3 Bio-char Application

Bio-char is a carbon-rich material generated by the pyrolysis of organic biomass in a low-oxygen environment (Bolan *et al.* 2022) ^[10]. When applied to soils, biochar is highly stable and acts as a long-term carbon reservoir.

Biochar enhances the properties of soil by increasing nutrient retention, water holding capacity, and microbial activity but resisting decomposition (Do Nascimento *et al.*, 2023) ^[23]. The benefits of using biochar include locking carbon into the soil, reducing greenhouse gas emissions, and lowering methane and nitrous oxide emissions (Lehmann *et al.* 2024) ^[66]. Biochar's porous structure enhances nutrient retention and reduces leaching; thus, nutrients are readily available to plants (Lehmann *et al.* 2006) ^[67]. It also increases crop yields because of enhanced soil fertility, which in turn leads to better plant growth and productivity. However, biochar has some challenges, including high production costs, because large-scale production is energy-intensive and expensive, and variability in properties, because its effectiveness depends on the feedstock type and production methods, which can be quite different.

3.4 Cover Cropping

Plant cover crops like legumes, grasses, or brassicas between the cycles of major crops to protect and enrich the soil (Fageria *et al.* 2005) ^[30]. They do that by preventing erosion, increasing organic matter, and raising the fertility of the soil (Doran *et al.* 1991) ^[25].

Cover crops absorb atmospheric carbon through photosynthesis, and their residues contribute to soil organic matter upon decomposition (Kuz'yakov & Cheng, 2001) ^[52]. They offer several benefits, such as nitrogen fixation by leguminous cover crops, which enrich the soil and reduce the need for synthetic fertilizers. Cover crops also reduce nutrient leaching by capturing residual nutrients, preventing them from being washed away Poeplau C, Don A, (2015)

[84]. Moreover, their dense growth suppresses weeds, lowering herbicide requirements. However, they present challenges, such as increased management complexity, as careful planning is required for their timing and selection within crop rotations, and potential water competition in water-scarce areas, where they may compete with main crops for moisture.

3.5 Improved Nutrient Management

Nutrient Management Best Practices Optimize the timing and application of fertilizers and organic amendments to decrease emission of greenhouse gases and promote SOC storage (Alvarenga *et al.* 2020) [3].

Balanced nutrient management makes sure that crops get just enough amounts of fertilizers while minimizing excess that results in emission and runoff. Practices are made accordingly to maximize uptake and prevent waste. Managed fertilizers minimize the emission of this potent greenhouse gas (Smith *et al.* 2008) [106]. Adds stable organic matter in soils through organic amendment like compost, manure or crop residue.

4. Challenges

Maintaining soil health and nutrient balance requires close monitoring, including regular soil testing and real-time assessments, which demand technical expertise and instrumental support. Education of the farmers on adopting new techniques is required for effective implementation of nutrition management programs.

An integrated package of strategies is essential for improved effectiveness, as these practices are not mutually exclusive (Pulleman *et al.* 2000) [89]. Implementing multiple approaches together would yield greater benefits than applying each practice separately. For instance, conservation tillage in combination with cover cropping maximizes soil organic matter and minimizes erosion (Fageria, 2012) [29]. In the same way, the integration of agroforestry with bio-char application enhances both above-ground and below-ground carbon sequestration (Kwiatkowska, 2018) [53]. Improved nutrient management complements these strategies by enhancing soil fertility and reducing emissions, making it a synergistic approach to sustainable land management Six *et al.* 2002) [103].

4.1 Better Soil Health

Soil health is the backbone of productive and sustainable agriculture (Van Groenigen *et al.* 2017) [114]. Carbon sequestration increases soil organic matter, which enhances physical, chemical, and biological properties of the soil (Shahane AA, Shivay YS, 2021) [100].

Carbon sequestration is a win-win approach toward solving climate change, maintaining agricultural productivity, and enhancing soil health (Raihan A, 2023) [90]. Its co-benefits emphasize the interconnectedness of environmental, agricultural, and economic systems Lal R, (2004) [64]. By acknowledging and taking advantage of these benefits, policymakers, researchers, and farmers can develop resilient agricultural systems that support global sustainability goals (Nazir *et al.* 2024) [80].

Organic carbon-rich soils retain water better, decreasing the extent of water stress on crops. Soil structure, too, improves, so the rate of infiltration enhances with minimal surface runoff and efficient retention of water (Bot *et al.* 2005) [13]. It is a source of nutrient supply by serving as a reservoir to

plant available nutrients through microbials. Enhanced cation exchange capacity increases nutrient holding capacities that decrease dependence on inorganic fertilizers (Osman KT, 2013) [82]. Organic matter helps in binding the soil particles. These aggregates are stable enough to resist wind and water action causing erosion (Elbasiouny *et al.* 2022) [28]. Improved vegetation cover reduces the physical impact of the rainfall and runoff (Murphy BW, 2015) [78]. Carbon-enriched soils sustain diverse microbial populations, which enhance nutrient cycling and disease suppression.

4.2 Enhanced Agricultural Productivity

Carbon sequestration directly impacts agricultural productivity by improving soil conditions and supporting sustainable farming practices (Lal R *et al.* 2007) [62]. Enhanced soil fertility increases uptake of nutrients, thereby contributing to increased yield levels as well as minimized negative impacts due to drought and maintaining consistencies in productivity (Mukherjee D, 2013) [77]. There is also organic carbon preservation in soils at high contents, thus implying more use in the long term without necessarily degrading further (Mahmud *et al.* 2021) [71]. Applications such as agroforestry and cover cropping reduce income stream diversities that in turn increase resilience to either market or climatic shock (Tooche EC, 2018) [113]. Also, carbon-enriched soils promote natural nutrient cycling; the dependence on chemical fertilizers and irrigation is reduced, lowering the cost of production.

4.3 Climate Change Mitigation

Soils constitute one of the largest carbon sinks on Earth. Carbon sequestration within agricultural soils directly deals with issues associated with climate change through greenhouse gas reduction in the atmosphere (Rosenzweig C, & Hillel D, 2000) [95] and (Lal R, Follett RF, 2009) [61]. Carbon sequestration removes CO₂ from the atmosphere, storing it as stable organic matter in soils and helping to balance emissions from other sectors, contributing to net-zero carbon targets. By reducing CO₂ levels, it mitigates the greenhouse effect, stabilizing global temperatures and decreasing the intensity and frequency of climate extremes such as droughts and floods (Khalil MI, Osborne BA, & Winger A, 2024) [49]. Bio-char application and improved nutrient management decrease methane (CH₄) and nitrous oxide (N₂O) emissions Rounsevell *et al.* 1999) [96], which are more potent than CO₂. Carbon-rich soils support healthy ecosystems by acting as a buffer against climate variability, including shifts in precipitation patterns and increasing temperatures (Hessen DO, Vandvik V, 2022) [41].

The co-benefits of carbon sequestration include broader environmental and socio-economic benefits. Agroforestry and cover cropping practices are linked to biodiversity conservation by creating habitats for various plant and animal species, thus enhancing ecological balance (Malhi *et al.* 2002) [73]. Carbon-enriching practices also reduce runoff and nutrient leaching, which protects water bodies from eutrophication and pollution. These practices enhance the economic resilience of farmers through an improvement in yield and reduced reliance on costly inputs, hence maximizing profitability and financial stability. In addition, they enrich soil fertility and productivity, therefore providing consistent food supply in the growing global population demands.

5. Difficulties and Limitations of Carbon Sequestration in Agricultural Soils

Although the practice has a number of advantages, carbon sequestration in soils faces many technical, economic, policy-related, and environmental uncertainties that will limit its adoption and effectiveness.

While the challenges and limitations of carbon sequestration in agricultural soils are significant, they are not insurmountable. Concerted efforts by governments, researchers, and the agricultural community can work to address these barriers and unlock the full potential of soils as a tool for climate mitigation and sustainable development (Nair *et al.* 2009) ^[79] and (Janzen HH, 2015) ^[45].

5.1 Measurement and Verification

Measuring the accumulation or decline in soil organic carbon (SOC) over time is a crucial yet challenging task in carbon sequestration (Post *et al.*, 2001) ^[86]. One of the main issues is the complexity of measurement, as SOC levels vary spatially and temporally depending on soil type, management practices, and environmental conditions. Accurate measurement requires advanced technologies, such as soil sampling, remote sensing, and modeling, which can be labor- and cost-intensive (Abdulraheem *et al.*, 2023) ^[2]. Another challenge is the lack of standardized protocols for measuring and verifying changes in SOC across different regions and projects. The variation in these protocols limits the reliability of baselines and the ability to assess progress over time (Jandl *et al.*, 2014) ^[44]. Additionally, there is uncertainty in carbon permanence, as sequestered carbon may be lost due to soil disturbances, land use or land cover changes, or climatic factors, making long-term verification difficult.

5.2 Economic Constraints

The economics of conducting carbon sequestration activities often presents significant barriers to farmers and landowners (Sautter *et al.*, 2011) ^[98]. One of the major challenges is that most of the practices involved require investments in equipment, materials, and labor. Practices such as adopting no-till farming, applying biochar, and implementing agroforestry all demand these investments. These early costs are too high for the smallholder farmers to cover without external support (Migadde, A., 2020) ^[75]. Slow financial payback is another drawback: carbon sequestration advantages like improved soil fertility and higher crop productivity usually occur over time, and such benefits are less appealing to those who want their investments to yield faster returns (Reid *et al.*, 2020) ^[93]. Limited market incentives such as carbon credits and payments for ecosystem services are often not available or sufficient to compensate for the cost of adoption, particularly in developing regions (Six *et al.* 2006) ^[104].

5.3 Policy and Incentives

Supportive policies and incentives are crucial for the wide-scale adoption of carbon sequestration practices, but these are often absent or inadequately implemented (Villa JA, Bernal B, 2018) ^[116]. Among the main challenges is the lack of adequate policy frameworks, since many regions have no clear policies on sustainable soil management or financial incentives for carbon sequestration. As a consequence, little guidance or assistance is extended to farmers to pursue these measures on their farmlands (Marland *et al.*, 2001) ^[74].

There is also not well-defined property rights such that the land tenure system discourages long-term soil health investment, especially considering that in many cases of rented and communal lands the farmer benefits from the improvements aren't captured. In the same context, the deficiency of research and development owing to less fund availability makes the region-specific practices' investigation with the possibility of carbon sequestration into an impasse, causing retardation in developing effective solutions.

5.4 Climate Variability

Climatic conditions, which are quite uncertain, significantly influence the efficacy of carbon sequestration practices (Di Sacco *et al.*, 2021) ^[19]. Extreme weather events include droughts, floods, and storms, which will often interrupt the processes, thereby causing SOC loss and instability of stored carbon (Bai *et al.* 2019) ^[5]. For example, heavy rainfall can cause erosion, while prolonged droughts limit biomass production and result in lower inputs of organic matter into the soil. The other challenge is regional climate disparity, where practices that perform well in one climate zone may not perform well in others due to differences in temperature, rainfall, and growing seasons. Furthermore, future conditions are uncertain due to climate change, which makes it hard to predict how ecosystems and soils will react to management practices, thus complicating long-term planning (Vermeulen *et al.*, 2012) ^[115].

To address these challenges, innovative approaches, supportive policies, and farmer-focused initiatives are required. Improved measurement techniques, such as satellite imagery, machine learning, and soil sensors, can improve the accuracy and efficiency of SOC monitoring. Incentives such as subsidies, grants, and carbon credits help to offset the high front-end costs and can help stimulate adoption. Policy clarity and legal frameworks should facilitate land management practices that are considered sustainable and provide tools and knowledge to farmers. Other adaptations include using drought-resistant crops and erosion control methods in climate adaptation strategies, reducing impacts from climate variability, and helping carbon sequestration practices succeed (Bai *et al.* 2019) ^[5].

6. Policy Recommendations and Future Directions for Carbon Sequestration in Agricultural Soils

For full utilization of the potential of agricultural soils in carbon sequestration, a comprehensive policy framework and forward-looking strategies are necessary (Wade *et al.* 2022) ^[117]. Such measures must take into account economic, technical, and social barriers to innovation and collaboration.

Supportive policies, capacity building, research, and integrated approaches are some of the ways in which carbon sequestration in agricultural soils can be fully exploited (Kimble JM, Lal R, Follett RF, 2016) ^[51]. Such efforts would not only mitigate climate change but also enhance sustainable farming practices, improve food security, and increase rural livelihoods (Lal R, Negassa W, Lorenz K, 2015) ^[64]. With a focus on overcoming current challenges and pursuing forward-looking strategies, the agricultural sector can become an ally in the global struggle against climate change (Powlson *et al.* 2014) ^[87]. Some key policy recommendations and future directions are as follows:

6.1 Policy Interventions

Well-designed policy interventions can facilitate incentives and motivation for the farming community and its stakeholders in practicing carbon sequestration.

Government support is essential to popularize carbon sequestration through the use of incentives, including subsidies for techniques such as conservation tillage, agroforestry, and application of biochar (Corbeels *et al.*, 2019) ^[17]. Other inducements, including reduced taxes, low-interest loans, and direct payments to promote the storage of soil carbon, may be helpful in its adoption (Smith P, 2008) ^[108]. This also may be included in the carbon credit system so that there will be economic incentives for farmers. The improvement in transparency and access in carbon credit markets allows farmers to realize the value of carbon that they sequester through equitable access (Chute *et al.*, 2022) ^[16]. Registration and verification processes could be simplified to make access to these markets easier for smallholder farmers (Döring D, 2024) ^[26]. Crop failure insurance or insurance policies that are in place against extreme weather events reduce risks from the adoption of new practices. Public-private partnerships sharing the risks will promote more participation by farmers.

Clear land tenure policies ensure farmers and landowners can gain from investments in soil health and carbon sequestration. Moreover, regulations to prevent land conversion to short-term uses, such as urban development, are necessary to preserve long-term carbon storage (Follett RF, Reed DA, 2010) ^[33].

6.2 Capacity Building

Proper education and training of farmers and land managers are essential to successfully implement carbon sequestration practices.

Workshops, field demonstrations, and online training sessions should be conducted for increasing awareness about the benefits and techniques of carbon sequestration (Kimble *et al.*, 2016) ^[51]. The educational material should be adapted to the local context by using local examples of soil types, crops, and climate. Extension should be offered to continue training and include soil testing and monitoring along with best management practices (Zerssa *et al.* 2021) ^[120]. More knowledge can then be spread through peer networking through cooperatives and at the local level by creating community-led programs (Chevallier *et al.*, 2024) ^[15]. Rewarding the adoption of sustainable agricultural practices inspires others. Local success stories build trust in new approaches, encouraging wider adoption (Rodriguez *et al.*, 2009) ^[94].

6.3 Research and Development

Investing in research and innovation is important to create low-cost, scalable, and region-specific solutions for carbon sequestration (Costa *et al.* 2021) ^[18].

The developing affordable tools and methods for measuring and verifying SOC requires development of low-cost sensors and remote sensing technologies, which is also the necessity of innovation in biochar and other soil amendments, ensuring its availability to small farmers (Raj *et al.*, 2023) ^[92]. Agro-climatic zones will be required to find out the local effective carbon sequestration practice. Also, traditional and indigenous knowledge systems that should match the sustainable land management goals must be researched and learned about. Research projects should be

developed to monitor the long-term impacts of carbon sequestration practices on soil health, crop yields, and greenhouse gas emissions. Advanced modeling tools can help predict outcomes and inform decision-making at both policy and farm levels (Lal R, Follett RF, 2009) ^[61]. Research institutes, universities and private companies should be engaged and collaborated to accelerate the development and deployment of innovative solutions.

6.4 Integrated Approaches

Multiple strategies can work synergistically to boost the overall efficiency and effectiveness of carbon sequestration efforts.

Include conservation tillage, agroforestry, cover crop, and nutrient management among integrated land-use plans, thereby emphasizing Agroecological approaches that balance both productivity, biodiversity, and carbon sequestration (Jhariya *et al.*, 2022) ^[46]. Use data-intensive platforms, such as mobile applications and GIS-based systems, to provide timely information on soil health, weather conditions, and best practices to farmers. Use blockchain technology for tracking environmental impacts transparently, where carbon credits may be utilized (Boruah *et al.*, 2024) ^[11]. Partner governments, NGOs, private firms, and local communities to share resources, knowledge, and responsibility. Provide coordination forums with a space for dialogue on harmonizing efforts and not duplicating each other. scaling up pilot programs scale up successful pilot projects into regional or national programs to increase their impact. Equitable scaling must capture the needs of small farmers, marginalized groups, and women farmers.

International Cooperation Strengthen international cooperation in exchange of knowledge, funding, and development of technologies for the purpose of carbon sequestration in soil. Ensure that carbon sequestration efforts are incorporated into nationally appropriate climate action plans such as through NDCs of Paris Agreement. Engage the private sectors in business through sustainable agriculture and offsetting carbon activities as one of the key components of corporate social responsibility Kell DB, (2011) ^[48]. Educate the public on the role of soils in climate mitigation in order to build public support for appropriate policies and programs.

7. Conclusion

Carbon sequestration in agricultural soils represents an important opportunity to address the twin challenges of climate change and agricultural sustainability. Capturing and storing atmospheric carbon dioxide in soils reduces global warming while improving soil health, boosting agricultural productivity, and enhancing resilience to environmental stresses. Its full potential can only be realized through efforts across scientific innovation, policy-making, and engagement with farmers and local communities.

As a nature-based solution, soil carbon sequestration is cost-effective and scalable for reducing greenhouse gas concentrations. It supports net-zero emissions targets in line with global climate goals, such as those presented in the Paris Agreement. Improving soil organic carbon (SOC) levels also addresses the urgent issues of soil degradation, desertification, and declining agricultural productivity.

Organic carbon-enriched soils exhibit better water retention, nutrient availability, and microbial activity. Thus, agricultural systems are made more fertile and resilient. It

benefits the farmer directly in terms of increased crop yields, reduced dependency on synthetic inputs, and long-term sustainability. Healthier soils act as a buffer against extreme weather events like droughts and floods, thereby increasing resilience to climate variability.

However, the challenges are such as complexities in measurement, economic constraint, and variable climatic conditions. The complete eradication of such challenges involves both scientific innovations in cutting the cost of measuring and monitoring SOC as well as support policies by governments. Subsidies, carbon credits, and regulations on land use might be included as such support policies.

Active engagement from farmers is essential for the success of sequestration practices. Tailor-made education and training programs, along with technical and financial support, can empower farmers to adopt and sustain these practices.

A collaborative approach is needed, involving multidisciplinary stakeholders such as policymakers, scientists, farmers, private sector actors, and international organizations. Multi-stakeholder platforms can foster an innovation-friendly environment, resource mobilization, and equitable sharing of carbon sequestration benefits. Integration of carbon sequestration with other sustainable land management practices like agroforestry, conservation agriculture, and improved nutrient management will help amplify its effectiveness. The use of digital tools, such as remote sensing and data-driven platforms, will also increase the scalability and precision of these initiatives.

To make carbon sequestration efforts effective, the focus of future efforts should be on building research and development capabilities through region-specific studies that help in identifying the best practices of sequestration under various agro-climatic conditions (Jandl *et al.* 2007). Successful models developed in pilot projects should be scaled up to regional and national programs that are also representative and responsive to local needs. Transparent carbon credit systems and payment mechanisms should be developed to financially incentivize farmers for their contribution. Public awareness should be built on the role of soils in climate change mitigation, creating support for policies and investments.

Carbon sequestration in agricultural soils is not only a climate-mitigation strategy but also a way toward sustainable agriculture, better food security, and enhanced livelihoods for rural communities. Despite challenges, they are conquerable through innovation, coherent policies, and equity and inclusivity commitment. In enabling the environment, global cooperation, and promoting collaboration in agriculture, the latter will assist in the attainment of climate goals while guaranteeing a sustainable future for the generations to come.

8. References

1. Abbas F, Hammad HM, Ishaq W, Farooque AA, Bakhat HF, Zia Z, *et al.* A review of soil carbon dynamics resulting from agricultural practices. *J Environ Manage.* 2020;268:110319.
2. Abdulraheem MI, Zhang W, Li S, Moshayedi AJ, Farooque AA, Hu J. Advancement of remote sensing for soil measurements and applications: A comprehensive review. *Sustainability.* 2023;15(21):15444.
3. Alvarenga P, Carneiro JP, Fangueiro D, Cordovil CM, Bernal MP. Managing organic amendments in agroecosystems to enhance soil carbon storage and mitigate climate change. In: *Climate change and soil interactions.* Elsevier, 2020, p. 89-141.
4. Andersen MS, Bonnis G. Climate mitigation co-benefits from sustainable nutrient management in agriculture: Incentives and opportunities, 2021.
5. Bai X, Huang Y, Ren W, Coyne M, Jacinthe PA, Tao B, *et al.* Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Glob Change Biol.* 2019;25(8):2591-606.
6. Balesdent J, Chenu C, Balabane M. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil Tillage Res.* 2000;53(3-4):215-30.
7. Batjes NH. Mitigation of atmospheric CO₂ concentrations by increased carbon sequestration in the soil. *Biol Fertil Soils.* 1998;27:230-5.
8. Bhattacharya SS, Kim KH, Das S, Uchimiya M, Jeon BH, Kwon E, *et al.* A review on the role of organic inputs in maintaining the soil carbon pool of the terrestrial ecosystem. *J Environ Manage.* 2016;167:214-27.
9. Blanco H, Lal R. Tillage Systems. In: *Soil Conservation and Management.* Cham: Springer Nature Switzerland, 2023, p. 127-57.
10. Bolan N, Hoang SA, Beiyuan J, Gupta S, Hou D, Karakoti A, *et al.* Multifunctional applications of biochar beyond carbon storage. *Int Mater Rev.* 2022;67(2):150-200.
11. Boruah T, Kalita M, Hasnu S, Das KS, Singh R, Nayik GA. Role of Digital. Novel Approach to Sustainable Temperate Horticulture, 2024, p. 116.
12. Bossio DA, Patton CSC, Ellis PW, Fargione J, Sanderman J, Smith P, *et al.* The role of soil carbon in natural climate solutions. *Nat Sustain.* 2020;3(5):391-398.
13. Bot A, Benites J. The importance of soil organic matter: Key to drought-resistant soil and sustained food production. *Food Agric Org.* 2005(80).
14. Carter MR. Conservation tillage in temperate agroecosystems. CRC Press, 2017.
15. Chevallier R, Gosling A, Cramer L. Farmer-led Adaptation: Best Practice Case Studies, 2024.
16. Chute K, Cannady S, Davis W, Sain C. Agricultural Carbon Offset Market Development: Barriers & Opportunities from the Farmer Perspective, 2022.
17. Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E. The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. *Soil Tillage Res.* 2019;188:16-26.
18. Costa C, Seabauer M, Schwarz B, Dittmer K, Wollenberg EK. Scaling soil organic carbon sequestration for climate change mitigation, 2021.
19. Sacco DA, Hardwick KA, Blakesley D, Brancalion PH, Breman E, Cecilio Rebola L, *et al.* Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Glob Change Biol.* 2021;27(7):1328-1348.
20. Dimassi B, Cohan JP, Labreuche J, Mary B. Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France. *Agric Ecosyst Environ.* 2013;169:12-20.

21. Dioxide AC. The Global Carbon Cycle. Department of Energy ER-0239, Washington, 1985.
22. Discusses the "4 per mille" initiative and its implications for global soil carbon sequestration, 2021.
23. Nascimento DÍV, Fregolente LG, Pereira DAAP, Nascimento DCDV, Mota JCA, Ferreira OP, *et al.* Biochar as a carbonaceous material to enhance soil quality in drylands ecosystems: A review. *Environ Res.* 2023;233:116489.
24. Doetterl S, Berhe AA, Nadeu E, Wang Z, Sommer M, Fiener P. Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth Sci Rev.* 2016;154:102-22.
25. Doran JW, Smith MS. Role of cover crops in nitrogen cycling. *Cover Crops Clean Water.* 1991;85:90.
26. Döring D. Strategic Niche Management for Levering the Blockchain Technology towards Scaling up the Financing of Nature-based Solutions through Voluntary Carbon Markets: A Case Study (Master's thesis), 2024.
27. Ebouel FJD, Betsi TB, Eze PN. Soil inorganic carbon: A review of global research trends, analytical techniques, ecosystem functions and critical knowledge gaps. *Catena.* 2024;242:108112.
28. Elbasiouny H, El-Ramady H, Elbehiry F, Rajput VD, Minkina T, Mandzhieva S. Plant nutrition under climate change and soil carbon sequestration. *Sustainability.* 2022;14(2):914.
29. Fageria NK. Role of soil organic matter in maintaining sustainability of cropping systems. *Commun Soil Sci Plant Anal.* 2012;43(16):2063-2113.
30. Fageria NK, Baligar VC, Bailey BA. Role of cover crops in improving soil and row crop productivity. *Commun Soil Sci Plant Anal.* 2005;36(19-20):2733-2757.
31. Ferdush J. Determining the Effects of Elevated Carbon Dioxide on Soil Acidification, Cation Depletion, and Soil Inorganic Carbon and Mapping Soil Carbons Using Artificial Intelligence. Mississippi State University, 2022.
32. Follett RF. Soil management concepts and carbon sequestration in cropland soils. *Soil Tillage Res.* 2001;61(1-2):77-92.
33. Follett RF, Reed DA. Soil carbon sequestration in grazing lands: societal benefits and policy implications. *Rangeland Ecol Manage.* 2010;63(1):4-15.
34. Freibauer A, Rounsevell MDA, Smith P, Verhagen J. Carbon sequestration in the agricultural soils of Europe. *Geoderma.* 2004;122(1):1-23.
35. Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, *et al.* Betting on negative emissions. *Nat Clim Change.* 2014;4(10):850-3.
36. Ghosh S, Saha A, Kumar S, Pathania S. Regenerative Agriculture for Climate Change Mitigation and Food Security. In: *Regenerative Agriculture for Sustainable Food Systems.* Singapore: Springer Nature Singapore, 2024, p. 83-133.
37. Grimm R, Behrens T, Märker M, Elsenbeer H. Soil organic carbon concentrations and stocks on Barro Colorado Island-Digital soil mapping using Random Forests analysis. *Geoderma.* 2008;146(1-2):102-113.
38. Guo LB, Gifford RM. Soil carbon stocks and land use change: a meta-analysis. *Glob Change Biol.* 2002;8(4):345-360.
39. Hamza MA, Anderson WK. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil Tillage Res.* 2005;82(2):121-145.
40. Hendrickson O. Influences of global change on carbon sequestration by agricultural and forest soils. *Environ Rev.* 2003;11(3):161-92.
41. Hessen DO, Vandvik V. Buffering climate change with nature. *Weather Climate Soc.* 2022;14(2):439-450.
42. Hussain S, Hussain S, Guo R, Sarwar M, Ren X, Krstic D, *et al.* Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants.* 2021;10(10):2001.
43. Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, *et al.* How strongly can forest management influence soil carbon sequestration? *Geoderma.* 2007;137(3-4):253-268.
44. Jandl R, Rodeghiero M, Martinez C, Cotrufo MF, Bampa F, Wesemael VB, *et al.* Current status, uncertainty and future needs in soil organic carbon monitoring. *Sci Total Environ.* 2014;468:376-383.
45. Janzen HH. Beyond carbon sequestration: Soil as conduit of solar energy. *Eur J Soil Sci.* 2015;66(1):19-32.
46. Jhariya MK, Raj A, Banerjee A, Meena RS, Bargali SS, Kumar S, *et al.* Plan and policies for soil organic carbon management under agroforestry system. In: *Plans and Policies for Soil Organic Carbon Management in Agriculture.* Singapore: Springer Nature Singapore, 2022, p. 191-219.
47. Jobbágy EG, Jackson RB. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol Appl.* 2000;10(2):423-436.
48. Kell DB. Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. *Ann Bot.* 2011;108(3):407-418.
49. Khalil MI, Osborne BA, Wingler A. Towards net zero emissions without compromising agricultural sustainability: What is achievable? *Nutr Cycl Agroecosyst.* 2024;128(3):283-91.
50. Khangura R, Ferris D, Wagg C, Bowyer J. Regenerative agriculture-A literature review on the practices and mechanisms used to improve soil health. *Sustainability.* 2023;15(3):2338.
51. Kimble JM, Lal R, Follett RF, editors. *Agricultural practices and policies for carbon sequestration in soil.* CRC Press, 2016.
52. Kuzyakov Y, Cheng W. Photosynthesis controls of rhizosphere respiration and organic matter decomposition. *Soil Biol Biochem.* 2001;33(14):1915-1925.
53. Kwiatkowska-Malina J. Qualitative and quantitative soil organic matter estimation for sustainable soil management. *J Soils Sediments.* 2018;18:2801-2812.
54. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science.* 2004;304(5677):1623-167.
55. Lal R. Soil carbon sequestration to mitigate climate change. *Geoderma.* 2004;123(1-2):1-22.
56. Lal R. Carbon sequestration. *Philos Trans R Soc B Biol Sci.* 2008;363(1492):815-830.
57. Lal R. Soil carbon management and climate change. *Carbon Manage.* 2013;4(4):439-462.

58. Lal R. Sequestering carbon and increasing productivity by conservation agriculture. *J Soil Water Conserv.* 2015;70(3):55A-62A.
59. Lal R. Soil health and carbon management. *Food Energy Secur.* 2016;5(4):212-222.
60. Lal R. Carbon cycling in global drylands. *Curr Clim Change Rep.* 2019;5:221-232.
61. Lal R, Follett RF, editors. Soil carbon sequestration and the greenhouse effect. ASA-CSSA-SSSA, 2009.
62. Lal R, Follett RF, Stewart BA, Kimble JM. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Sci.* 2007;172(12):943-956.
63. Lal R, Monger C, Nave L, Smith P. The role of soil in regulation of climate. *Philos Trans R Soc B Biol Sci.* 2021;376(1834):20210084.
64. Lal R, Negassa W, Lorenz K. Carbon sequestration in soil. *Curr Opin Environ Sustain.* 2015;15:79-86.
65. Lather Y, Hyndavi SV. Agroecological approaches to soil management. *Soil.* 367.
66. Lehmann J, Joseph S, Editors. Biochar for environmental management: Science, technology and implementation. Taylor & Francis, 2024.
67. Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems-a review. *Mitig Adapt Strateg Glob Change.* 2006;11:403-427.
68. Lin AC. Making net zero matter. *Wash Lee Law Rev.* 2022;79:679.
69. Liu X, Wang S, Zhuang Q, Jin X, Bian Z, Zhou M, *et al.* A review on carbon source and sink in arable land ecosystems. *Land.* 2022;11(4):580.
70. Lorenz K, Lal R. Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *J Plant Nutr Soil Sci.* 2014;177(5):651-70.
71. Mahmud AA, Upadhyay SK, Srivastava AK, Bhojiya AA. Biofertilizers: A nexus between soil fertility and crop productivity under abiotic stress. *Curr Res Environ Sustain.* 2021;3:100063.
72. Malézieux E. Designing cropping systems from nature. *Agron Sustain Dev.* 2012;32:15-29.
73. Malhi Y, Meir P, Brown S. Forests, carbon and global climate. *Philos Trans R Soc Lond A Math Phys Eng Sci.* 2002;360(1797):1567-1591.
74. Marland G, McCarl BA, Schneider U. Soil carbon: policy and economics. *Clim Change.* 2001;51(1):101-117.
75. Migadde A. Carbon farming opportunities for crop cooperatives in Uganda. Van Hall Larenstein, 2020.
76. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, *et al.* Soil carbon 4 per mille. *Geoderma.* 2017;292:59-86.
77. Mukherjee D. Nutrient use efficiency for maximization of crop productivity. In: *Advances in plant physiology- An international treatise series.* Jodhpur, India: Scientific Publishers, 2013, p. 173-209.
78. Murphy BW. Impact of soil organic matter on soil properties: A review with emphasis on Australian soils. *Soil Res.* 2015;53(6):605-635.
79. Nair PR, Nair VD, Kumar BM, Haile SG. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environ Sci Policy.* 2009;12(8):1099-111.
80. Nazir MJ, Li G, Nazir MM, Zulfiqar F, Siddique KH, Iqbal B, *et al.* Harnessing soil carbon sequestration to address climate change challenges in agriculture. *Soil Tillage Res.* 2024;237:105959.
81. Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. *Methods Soil Anal Part 3 Chem Methods.* 1996;5:961-1010.
82. Osman KT, Osman KT. Plant nutrients and soil fertility management. In: *Soils: Principles, properties and management,* 2013, p. 129-59.
83. Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. *Nature.* 2016;532(7597):49-57.
84. Poeplau C, Don A. Carbon sequestration in agricultural soils via cultivation of cover crops-A meta-analysis. *Agric Ecosyst Environ.* 2015;200:33-41.
85. Post WM, Kwon KC. Soil carbon sequestration and land-use change: processes and potential. *Glob Change Biol.* 2000;6(3):317-327.
86. Post WM, Izaurralde RC, Mann LK, Bliss N. Monitoring and verifying changes of organic carbon in soil. *Clim Change.* 2001;51(1):73-99.
87. Powlson DS, Stirling CM, Jat ML, Gerard BG, Palm CA, Sanchez PA, *et al.* Limited potential of no-till agriculture for climate change mitigation. *Nat Clim Change.* 2014;4(8):678-683.
88. Powlson DS, Whitmore AP, Goulding KW. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *Eur J Soil Sci.* 2011;62(1):42-55.
89. Pulleman MM, Bouma J, Essen VEA, Meijles EW. Soil organic matter content as a function of different land use history. *Soil Sci Soc Am J.* 2000;64(2):689-93.
90. Raihan A. A review of climate change mitigation and agriculture sustainability through soil carbon sequestration. *J Agric Sustain Environ.* 2023;2997:271X.
91. Raj A, Jhariya MK, Yadav DK, Banerjee A, Meena RS. Agroforestry: A holistic approach for agricultural sustainability. In: *Sustainable Agriculture, Forest, and Environmental Management,* 2019, p. 101-31.
92. Raj P, Maurya PK, Darjee S, Rout S. Sustainable farmer-friendly technologies for soil management. *Adv Farming Technol,* 2023, 34.
93. Reid WV, Ali MK, Field CB. The future of bioenergy. *Glob Change Biol.* 2020;26(1):274-286.
94. Rodriguez JM, Molnar JJ, Fazio RA, Sydnor E, Lowe MJ. Barriers to adoption of sustainable agriculture practices: Change agent perspectives. *Renew Agric Food Syst.* 2009;24(1):60-71.
95. Rosenzweig C, Hillel D. Soils and global climate change: Challenges and opportunities. *Soil Sci.* 2000;165(1):47-56.
96. Rounsevell MDA, Evans SP, Bullock P. Climate change and agricultural soils: impacts and adaptation. *Clim Change.* 1999;43(4):683-709.
97. Sanaullah M, Afzal T, Shahzad T, Wakeel A. Soil organic carbon sequestration and climate change, 2022.
98. Sautter JA, Czap NV, Kruse C, Lynne GD. Farmers' decisions regarding carbon sequestration: A metaeconomic view. *Soc Nat Resour.* 2011;24(2):133-147.
99. Schlesinger WH, Amundson R. Managing for soil carbon sequestration: Let's get realistic. *Glob Change Biol.* 2019;25(2):386-389.

100. Shahane AA, Shivay YS. Soil health and its improvement through novel agronomic and innovative approaches. *Front Agron.* 2021;3:680456.
101. Shahzad K, Sintim H, Ahmad F, Abid M, Nasim W. Importance of carbon sequestration in the context of climate change. In: *Building Climate Resilience in Agriculture: Theory, Practice, and Future Perspective*, 2022, p. 385-401.
102. Singh BP, Setia R, Wiesmeier M, Kunhikrishnan A. Agricultural management practices and soil organic carbon storage. In: *Soil Carbon Storage*. Academic Press, 2018, p. 207-44.
103. Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil.* 2002;241:155-176.
104. Six J, Frey SD, Thiet RK, Batten KM. Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Sci Soc Am J.* 2006;70(2):555-569.
105. Smith P. Carbon sequestration in croplands: the potential in Europe and the global context. *Eur J Agron.* 2004;20(3):229-236.
106. Smith P. Land use change and soil organic carbon dynamics. *Nutr Cycl Agroecosyst.* 2008;81:169-178.
107. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, *et al.* Greenhouse gas mitigation in agriculture. *Philos Trans R Soc B Biol Sci.* 2008;363(1492):789-813.
108. Sommer R, Bossio D. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *J Environ Manage.* 2014;144:83-87.
109. Swarup A, Manna MC, Singh GB. Impact of land use and management practices on organic carbon dynamics in soils of India. In: *Global Climate Change and Tropical Ecosystems*, 2019, p. 261-81.
110. Tan WF, Zhang R, Cao H, Huang CQ, Yang QK, Wang MK, *et al.* Soil inorganic carbon stock under different soil types and land uses on the Loess Plateau region of China. *Catena.* 2014;121:22-30.
111. Tiefenbacher A, Sandén T, Haslmayr HP, Miloczki J, Wenzel W, Spiegel H. Optimizing carbon sequestration in croplands: A synthesis. *Agronomy.* 2021;11(5):882.
112. Toensmeier E. *The carbon farming solution: A global toolkit of perennial crops and regenerative agriculture practices for climate change mitigation and food security*. Chelsea Green Publishing, 2016.
113. Toohey EC. Carbon sequestration: how much can forestry sequester CO₂. *For Res Eng Int J.* 2018;2(3):148-150.
114. Groenigen VJW, Kessel VC, Hungate BA, Oenema O, Powlson DS, Groenigen VKJ. Response to the letter to the editor regarding our viewpoint "Sequestering soil organic carbon: A nitrogen dilemma." *Environ Sci Technol.* 2017;51(20):11503-11504.
115. Vermeulen SJ, Campbell BM, Ingram JS. Climate change and food systems. *Annu Rev Environ Resour.* 2012;37(1):195-222.
116. Villa JA, Bernal B. Carbon sequestration in wetlands, from science to practice: An overview of the biogeochemical process, measurement methods, and policy framework. *Ecol Eng.* 2018;114:115-128.
117. Wade CM, Baker JS, Jones JP, Austin KG, Cai Y, de Hernandez AB, *et al.* Projecting the impact of socioeconomic and policy factors on greenhouse gas emissions and carbon sequestration in US forestry and agriculture. *J For Econ.* 2022;37(1):127-131.
118. Wiesmeier M, Urbanski L, Hobbey E, Lang B, von Lützow M, Marin-Spiotta E, *et al.* Soil organic carbon storage as a key function of soils-A review of drivers and indicators at various scales. *Geoderma.* 2019;333:149-162.
119. Wreford A, Ignaciuk A, Gruère G. Overcoming barriers to the adoption of climate-friendly practices in agriculture, 2017.
120. Zeressa G, Feyssa D, Kim DG, Löbermann EB. Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. *Agriculture.* 2021;11:192.
121. Zomer RJ, Bossio DA, Sommer R, Verchot LV. Global sequestration potential of increased organic carbon in cropland soils. *Sci Rep.* 2017;7(1):15554.
122. Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, *et al.* Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global and national carbon budgets. *Sci Rep.* 2016;6(1):29987.
123. Zuazo VHD, Pleguezuelo CRR, Flanagan D, Tejedo IG, Fernández JLM. Sustainable land use and agricultural soil. In: *Alternative Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation*, 2011, p. 107-92.