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The role of agriculture in carbon sequestration: management practices, determining factors, and challenges – a review

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ABSTRACT

Climate change, largely driven by rising concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), has become a major global concern. Agriculture contributes significantly to these emissions but also holds great potential as a carbon sink through the sequestration of carbon in soils and vegetation. Carbon sequestration in agricultural systems primarily occurs through biological processes that store atmospheric CO_2 in soil organic matter and plant biomass, thereby mitigating climate change while also enhancing soil fertility, biodiversity, and ecosystem resilience. Management practices such as conservation tillage, agroforestry, application of organic amendments, cover cropping, crop rotations, precision farming, and improved grazing systems have been shown to increase soil organic carbon (SOC) stocks and deliver multiple co-benefits, including improved soil structure, greater water retention, reduced erosion, and higher crop productivity. Despite these advantages, the widespread adoption of sequestration practices faces several challenges, including limited soil carbon storage capacity, the risk of carbon loss if practices are discontinued, high variability across soils and climates, costly and complex monitoring systems, insufficient policy and institutional support. Effective solutions depend on integrated efforts involving scientific research, policy development, and farmer participation. This study contributes to and achieves this goal through specific land and crop management practices that enhance the storage of organic carbon in soils and vegetation, reduce greenhouse gas (GHG) emissions, and improve overall ecosystem health.

Keywords: *Carbon sequestration, agriculture, soil organic carbon, carbon sink, climate change, climate resilience, greenhouse gases, sustainability, carbon stock, agricultural policy, ecosystem.*

Introduction

There is a concerning problem: rising levels of greenhouse gases (GHGs) in the atmosphere are causing climate change. Methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) are the three main greenhouse gases, playing a significant role in climate change. CO_2 is the most common and contributes the highest share, which is 65%, to global emissions. Since the industrial revolution, human activity has increased the atmospheric concentrations of CO_2, CH_4, N_2O, and CFC by 30%, 145%, and 15%, respectively [1]. There is a direct relation between carbon dioxide levels in the atmosphere and global temperatures.

Agriculture substantially contributes to greenhouse gas emission. However, it also has significant potential as a carbon sink through carbon sequestration. This can be achieved by reducing greenhouse gas emissions, especially carbon dioxide, and storing carbon in soil and plants. Soil carbon sequestration is recognized as one of the most effective strategies for mitigating climate change [2]. Another advantage of this approach is that it can also increase agricultural output [3]. This process not only helps fight climate change but also enhances soil health, agricultural productivity, and ecosystem resilience.

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Agriculture production systems play a vital role in the global carbon cycle. They act as both sources and sinks of greenhouse gases. Traditional farming methods have contributed to increased carbon emissions through deforestation and soil degradation, whereas sustainable agriculture presents a significant opportunity for carbon sequestration. Practices such as cover cropping, reduced tillage, organic amendments, and agroforestry can increase soil organic carbon stocks, enhance soil health, and mitigate the impacts of climate change [4]. However, the success of these practices relies on some factors such as soil type, environmental conditions, and management strategies; therefore, it is crucial to implement region-specific and context-sensitive strategies to maximize carbon sequestration in crop systems. As the focus on sustainable climate change mitigation grows, understanding the mechanisms of carbon sequestration in agricultural systems, along with their benefits and limitations, has become increasingly important [5]. The primary objective of this review study is to investigate strategies for enhancing the management of agricultural practices to improve the soil's capacity to sequester atmospheric carbon dioxide (CO_2) and support biomass production. This involves various management strategies that not only sequester carbon but also improve soil quality, increase agricultural production, and help combat climate change. This study will also review the factors that influence carbon sequestration, the benefits and co-benefits, and the challenges and limitations related to agriculture.

Mechanisms of carbon sequestration

Carbon sequestration is the method of trapping carbon dioxide from the atmosphere and retaining it in a stable form. It encompasses diverse techniques to remove and retain atmospheric CO_2, thereby mitigating climate change. These techniques are usually divided into four categories: biological, geological, technological, and industrial methods.

A. Biological carbon sequestration: Biological carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2) in biological systems such as plants, soils, and aquatic ecosystems, helping to reduce the impacts of climate change. Forests and vegetation absorb CO_2 through photosynthesis and store carbon in their biomass and soil. Aquatic ecosystems, including oceans, wetlands, and marine vegetation such as phytoplankton, seagrasses, and algae, are significant carbon sinks. However, they are threatened by acidification and warming. Biochar, produced from organic waste, sequesters carbon for the long term while also enhancing soil fertility. Microorganisms, including algae and bacteria, fix carbon through various metabolic processes. Microbial and algal carbon fixation is substantial and emerging technologies, such as microbial electrolysis carbon capture (MECC), offer innovative methods for capturing carbon dioxide [6].

B. Geological carbon sequestration: Geological carbon sequestration is an effective method for reducing atmospheric CO_2 levels by injecting carbon dioxide into deep geological formations for long-term storage [7]. The main trapping mechanisms include: (i) stratigraphic trapping, where CO_2 is stored below impermeable cap rock layers in porous rocks, preventing it from moving upward; (ii) residual trapping, where CO_2 is trapped as small droplets within the pore spaces due to capillary forces; (iii) solubility trapping, which involves dissolving CO_2 in formation waters, creating denser brine that improves storage stability; and (iv) mineral trapping, which involves a chemical reaction between dissolved CO_2 and rock minerals to form stable carbonate minerals, ensuring permanent storage over long geological periods.

C. Technological carbon sequestration: Technological carbon sequestration uses engineered methods to capture and store CO_2, which helps reduce climate change. Key approaches include Direct Air Capture (DAC) that employs materials like covalent organic frameworks for efficient CO_2 removal, enhanced weathering that speeds up mineral reactions to create stable carbonates, CO_2-Plume Geothermal (CPG) that links CO_2 storage with geothermal energy production, and hydrothermal carbonization that changes wet biomass into stable, carbon-rich materials. These strategies deliver promising, scalable outcomes, accompanied by differing costs and advantages.

D. Industrial carbon sequestration: Industrial carbon sequestration captures CO_2 emissions from processes like cement, steel, and chemical production, preventing their release into the atmosphere. Technologies include post-combustion capture using amine-based solvents, oxy-fuel combustion to produce concentrated CO_2 streams, and pre-combustion capture in gasification plants. The captured CO_2 can be stored in deep geological formations. It can also be used for enhanced oil recovery, synthetic fuel production, and building materials such as carbon-cured concrete. This makes it an important strategy for reducing greenhouse gas emissions from industrial sources.

Management approaches for enhancing carbon sequestration

Improving carbon capture in farming is essential to help mitigate climate change. Several management strategies can effectively increase the storage of soil organic carbon (SOC), as discussed below.

I. Conservation agriculture: Reduced tillage in farming can significantly reduce climate change by increasing soil carbon storage. Conservation tillage, which includes no-till, ridge-till, and mulch-tillage systems, helps to increase soil organic carbon (SOC) storage by minimizing soil disturbance. Minimizing soil disturbance preserves surface crop residues, reduces breakdown of organic matter in the soil, and offers better protection for SOC within soil aggregates. Keeping residues also lowers erosion rates and encourages slow decomposition, which helps build up SOC over time. Furthermore, fewer disturbances maintain soil structure and support the microbial communities required for stabilizing persistent carbon pools [8]. Adoption of such practices in the United States could sequester 30–105 million metric tons of carbon annually [9]. In the Indo-Gangetic Plains, India, zero-tillage with residue retention stored 2.20 t ha^{-1} of soil organic carbon in the 0–15 cm layer over six years, while soil organic carbon was lost under conventional tillage [10]. In Central India, long-term conservation tillage over 4 to 15 years increased soil organic carbon by 22.2–38 [11]. Together, these findings show that conservation tillage is an effective method for improving soil organic carbon stocks and aiding climate change mitigation.

II. Agroforestry systems: Agroforestry systems (AFS) have emerged as an effective strategy for enhancing carbon sequestration through the integration of trees with crops and/or livestock. Such systems play a key role in conserving biodiversity, improving soil properties, and supporting long-term carbon storage in both tree biomass and soil. Incorporating trees into agricultural landscapes significantly improves soil carbon stocks compared to conventional farming. A meta-analysis reported that agroforestry systems sequester 25.34% more carbon than non-agroforestry systems, with agri-horticultural systems exhibiting the highest average soil carbon stock [9]. Agroforestry systems not only improve soil organic carbon but also store significant amounts of carbon in woody biomass, thereby contributing to long-term climate change mitigation. Region-specific studies show the differences in carbon sequestration potential across various agroforestry models. In Himalayan agroforestry systems, vegetation carbon densities range from 4.30 to 135.59 Mg C ha^{-1}, while soil carbon stocks vary from 9.37 to 186.0 Mg C ha^{-1} [12]. Assessed carbon storage in teak, acacia, and eucalyptus-based agroforestry systems of Bastar, Chhattisgarh, and reported that teak plantations exhibited the highest mean biomass carbon stock of 554.9 t C, with soil organic carbon content ranging from 0.112% to 0.913% in the top 100 cm of soil. These findings indicate that species selection, plantation design, and management practices are key to maximizing carbon sequestration potential [13].

III. Organic amendments: Organic amendments such as compost, manure, crop residues, biochar, green manure, mulch, vermicompost, and peat play a key role in soil carbon sequestration by increasing soil organic carbon (SOC) content and improving soil quality.

These inputs add organic carbon directly to the soil and promote stable carbon formation through enhanced microbial activity, nutrient cycling, and soil aggregation. Compost and manure contribute humic substances and labile carbon, which are transformed into stabilized soil organic carbon [14, 15]. Biochar, due to its stable nature, persists in soil for centuries to millennia and serves as a long-term carbon sink [16]. Crop residues supply decomposable organic matter and increase SOC pools [17]. Green manures incorporate fresh biomass and enhance microbial biomass carbon as well as SOC stabilization [18]. Mulching with organic materials reduces erosion, retains soil moisture, and, through its decomposition, adds organic matter to the soil and improves SOC content [19]. Vermicompost is a humified organic matter and, beneficial for soil microbes, accelerates the transformation of organic matter into stable SOC [20]. Peat lands are important natural carbon sinks and must be conserved to avoid significant carbon losses from drainage and degradation [21]. The systemic use and management of organic amendments provides a sustainable means to enhance carbon storage, improve soil health, and mitigate climate change.

IV. Cover cropping and crop rotation: Cover cropping refers to the practice of growing crops during fallow periods, which improves soil health, reduces erosion, and promotes carbon sequestration. Cover crops help store soil organic carbon by providing organic matter through their decomposition, improving soil aggregation, and stimulating soil microbial activity through root exudates of diverse crops. Cover crops improve soil aggregation, which promotes the formation of stable carbon protected within micro-aggregates and associated with minerals. Cover cropping increases SOC in surface soils by an average of 15.5%, with the highest accumulation rates observed in fine-textured soils [22].

Crop rotation refers to the alternation of different crops in a systematic manner across growing seasons. It not only supports carbon sequestration through the diverse root systems of crops but also reduces soil erosion and improves soil fertility. Diversity in root systems provides organic inputs at multiple soil depths. The inclusion of legumes in rotations enhances nitrogen fixation, thereby reducing the need for synthetic fertilizers and promoting carbon retention. According to the finding, long-term implementation of continuous crop rotation significantly increased SOC stocks by 10.05 Mg C ha^{-1}, highlighting the potential of this practice in carbon sequestration [23].

V. Precision agriculture and fertilizer management: Precision agriculture uses GPS, sensors, and data analytics–based systems to optimize farm input use through site-specific delivery of water, fertilizers, and pesticides in the right amounts. This approach not only minimizes indiscriminate input use but also improves crop productivity and reduces carbon emissions associated with fertilizer manufacturing and application. The balanced use of nitrogen and organic fertilizers enhances nitrogen use efficiency, reduces nitrous oxide (N_2O) emissions, promotes root biomass accumulation, and thereby increases soil organic carbon (SOC) stocks.

VI. Grassland-based livestock integration and grazing management: Sustainable grazing systems, such as rotational or adaptive multi-paddock (AMP) grazing, improve soil carbon storage by promoting deep-rooted grass growth and returning organic matter through manure and plant residues.

Adaptive grazing practices in North American grasslands can increase SOC and ecosystem resilience compared to continuous grazing. Adequate recovery periods for pasture vegetation improve root biomass, increase carbon deposition, and support nutrient cycling, while manure and urine inputs from livestock boost microbial activity and help stabilize soil carbon. Integration of crops with livestock recycles nutrients, reduces the need for external farm inputs, and strengthens soil health [24].

Factors influencing carbon sequestration in agriculture

Carbon sequestration in agricultural soils is governed by biophysical, socio-economic, and policy factors in an integrated manner, which determine the rate and stability of soil organic carbon (SOC) accumulation. Important factors include climate and weather conditions, soil type and texture, land use and cover, crop type and biodiversity, and supportive socio-economic systems.

I. Climate and weather conditions: Climate influences soil carbon dynamics by regulating crop productivity, microbial activity, and organic matter decomposition. Temperature and precipitation directly affect soil moisture and influence microbial-mediated carbon cycling [25]. Adequate soil moisture supports microbial decomposition and nutrient cycling, whereas drought reduces microbial activity and thereby limits carbon sequestration [26]. Selecting plant species adapted to a broad temperature range helps reduce environmental effects on sequestration by sustaining photosynthesis and carbon assimilation under variable climates [27].

II. Soil type and texture: Soil texture and mineral composition influence carbon stabilization mechanisms. Fine-textured soils, especially silty clay loams, have greater carbon storage potential due to their high surface area and aggregation capacity, which protect organic matter from microbial decomposition [28]. High clay content improves SOC stabilization by forming microaggregates and adsorbing chemicals onto mineral surfaces [29]. In contrast, coarse-textured sandy soils generally exhibit low SOC retention capacity due to low aggregation capacity and weaker organic matter binding.

III. Land use, land cover, crop type, and biodiversity: Land use and land cover changes significantly affect SOC stocks by altering the balance between carbon inputs and outputs. The conversion of forests to croplands causes substantial losses of soil organic carbon, up to 42%, whereas converting croplands to pasture can increase soil organic carbon by about 19% [30]. Perennial systems, agroforestry, and grassland restoration enhance carbon inputs and reduce soil disturbance, supporting long-term sequestration.

Crop type and biodiversity further affect SOC through differences in root biomass, residue quality, and soil disturbance. Perennials and deep-rooting species (*e.g.,* alfalfa, sunflower) facilitate substantial carbon translocation into deeper soil layers, with reported SOC gains of 380 kg C ha^{-1} yr^{-1} in the 0–90 cm profile [31]. Diversified cropping systems, such as intercropping and crop rotations, improve soil aggregation and soil organic carbon content, with reported increases of up to 12.5% in macro-aggregate–associated carbon [32]. Legumes improve microbial biomass and structural stability, thereby promoting SOC accumulation [33].

IV. Socio-economic and policy factors: Financial support, government rules, and sharing of knowledge play a big role in farmers adopting carbon-friendly practices. Secure land tenure and long-term leases provide farmers with the confidence to invest in sustainable practices such as conservation agriculture, cover cropping, and biochar application. Policy instruments, including carbon pricing, subsidies, and payments for ecosystem services (PES), can accelerate adoption. Knowledge transfer through education and extension reduces barriers by equipping farmers with advanced carbon management skills [34]. Moreover, market-driven incentives, particularly consumer demand for eco-labeled and low-carbon products, strengthen the uptake of SOC-enhancing practices [35].

Benefits and co–benefits of carbon sequestration in agriculture

Carbon sequestration in agriculture offers several environmental, agronomic, and socio-economic benefits, making it an important method for sustainable land use and climate change mitigation by storing atmospheric CO_2 in soils and vegetation. Carbon sequestration enhances farm productivity and ecosystem resilience.

I. Climate change mitigation: Carbon sequestration is a key method for reducing climate change by lowering atmospheric CO_2, the main greenhouse gas responsible for global warming. Agricultural, forestry, and land-use practices that increase carbon storage can reduce emissions and support net-zero targets [36]. Storing carbon in soils, plants, and other reservoirs helps stabilize the climate and supports ecosystem services.

II. Soil health improvement: Enhancing soil organic carbon (SOC) through sequestration improves the soil's physical, chemical, and biological properties. Higher SOC supports stable soil aggregates, better porosity, and root growth while reducing compaction. It also increases water retention, boosting drought tolerance and lowering irrigation needs. SOC stimulates microbial activity, which improves nutrient availability, reduces reliance on synthetic fertilizers, and supports plant health. A diverse microbial community enhances soil fertility and disease resistance. These benefits improve long-term soil productivity and ecosystem stability [37].

III. Increased biodiversity and water holding capacity: Carbon sequestration practices such as cover cropping, agroforestry, compost application, and reduced tillage enhance biodiversity both above and below ground. Higher SOC supports diverse soil organisms that enhance nutrient cycling, fertility, and pest control. Aboveground, diversified cropping and habitat creation further enrich biodiversity. Increased SOC also improves soil structure, water infiltration, and storage, while reducing erosion and strengthening drought resilience. Collectively, these changes foster more stable and resilient agro ecosystems [8].

IV. Socio-economic gains for farmers: In addition to environmental benefits, carbon sequestration provides notable socio-economic advantages. Increasing SOC through practices like conservation tillage, cover crops, and organic amendments enhances soil fertility and crop productivity, thereby reducing reliance on expensive chemical inputs and improving farm profitability. Participation in carbon markets and payment for ecosystem services (PES) schemes offers further income opportunities. Enhanced soil water retention and fertility also build climate resilience, lowering the risks of droughts, floods, and other extreme events for both smallholder and large-scale farmers [38].

Challenges and limitations of carbon sequestration in agriculture

Agricultural carbon sequestration offers considerable promise for climate change mitigation; however, its widespread adoption is constrained by scientific uncertainties, technical barriers, economic limitations, and institutional weaknesses. Addressing these challenges requires integrated approaches that combine financial incentives, robust measurement systems, supportive policies, and active farmer engagement.

I. Spatial and temporal variability: The rate of soil carbon storage varies significantly with soil characteristics, climate, topography, and management practices. Such heterogeneity complicates the reliable estimation of SOC changes and makes it difficult to develop broadly applicable guidelines. Year-to-year weather changes make soil carbon storage difficult to predict, as rainfall and temperature influence crop growth, soil residues, and long-term carbon levels.

II. Saturation and equilibrium: Soil has a limited capacity to accumulate carbon, after which storage efficiency diminishes. For example, no-till farming can store carbon for 5–20 years before it levels off, while diverse crop rotations may add carbon for many decades [39]. This shows that soils can only store a limited amount of carbon, which makes it important to use flexible practices that preserve these benefits and support sustainable farming.

III. Reversibility: Soil carbon is not permanently sequestered and may be rapidly lost if conservation practices are discontinued. For example, moving from no-till back to regular plowing can release much of the stored carbon into the air, reducing its climate benefits [39]. This highlights the need for long-term commitment and supportive policies that encourage farmers to continue such practices.

IV. Policy and institutional gaps: Weak policies, limited funding, and institutional gaps slow the large-scale adoption of agricultural carbon sequestration. Even when technical knowledge is available, many farmers face barriers such as a lack of training programs, weak extension services, and poor access to incentives. Stronger institutions (such as well-funded extension systems, farmer cooperatives, and local resource centers) together with clear and consistent policies are crucial for building trust, reducing risks, and enabling wider adoption.

V. Monitoring, reporting, and verification (MRV): Affordable and accurate monitoring of soil organic carbon (SOC) is crucial for confirming carbon gains, supporting credit systems, and ensuring transparency. However, present monitoring, reporting, and verification (MRV) approaches are often costly, technically demanding, and limited in detecting small but important SOC changes. Advances in inexpensive measurement tools, remote sensing, and standardized protocols are needed to make sequestration efforts more scalable and better integrated into global climate policies [40].

Conclusions

Agriculture plays a dual role in climate change, acting as both a source of greenhouse gas emissions and a potential sink through carbon sequestration. Sustainable practices such as conservation tillage, agroforestry, organic amendments, crop rotations, precision farming, and improved grazing management can enhance soil organic carbon and biomass storage, while also improving soil health, biodiversity, water retention, and farm productivity. Despite these benefits, challenges such as soil carbon saturation, reversibility of stored carbon, spatial variability, high monitoring costs, and weak policy support limit large-scale adoption. Overcoming these barriers requires region-specific management, farmer incentives, robust policies, and affordable monitoring systems. Strengthening carbon sequestration in agriculture is therefore not only a vital climate mitigation strategy but also a pathway toward sustainable farming and resilient food systems.

Authors' contributions: Kuldeep conceived the idea for the review, performed the literature search and drafted the initial draft of the manuscript. Vivek Kumar Singhal contributed to editing, critical revisions and overall refinement of the paper. Preeti Laxmi Dhruw helped in searching and collecting the documents. All authors reviewed and approved the final form of the manuscript.

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Future scope of the study - Further research is required to understand the complex interactions between soil, crop type, and climate in determining carbon sequestration efficiency. Strengthening data-driven assessments and developing supportive policy mechanisms will be crucial to applying scientific knowledge effectively in climate change.

Future research directions in the field of agriculture's role in carbon sequestration should focus on several key areas to enhance understanding and implementation: (1) long-term effects of agricultural diversification; (2) technological advancements in monitoring; (3) agroforestry and soil management practices; (4) policy and economic incentives; (5) climate-smart agriculture; (6) regional and context-specific studies.

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