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Carbon sequestration and soil health management under organic farming

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Abstract
Organic farming is increasingly recognized as a sustainable agricultural system that enhances soil health and contributes to climate change mitigation through carbon sequestration. Soil organic carbon (SOC) is a critical component of soil fertility, influencing nutrient cycling, microbial activity, soil structure, and ecosystem stability. Organic farming practices such as compost application, green manuring, crop rotation, cover cropping, and reduced use of synthetic agrochemicals promote the accumulation and stabilization of SOC in soils. These practices improve the physical, chemical, and biological properties of soil, including aggregate stability, water-holding capacity, nutrient availability, and microbial diversity. Enhanced microbial activity under organic systems further supports carbon transformation and long-term storage in soil. This review highlights recent advances in understanding the mechanisms of carbon sequestration and soil health management under organic farming. It also discusses the role of agro ecological interventions and conservation practices in improving soil resilience and sustainability. Nevertheless, organic farming represents a promising strategy for restoring degraded soils, improving agricultural sustainability, and reducing atmospheric carbon dioxide concentrations. Long-term research and policy support are essential to maximize its effectiveness in sustainable land management and climate change mitigation.

Keywords: Soil organic carbon, carbon sequestration, organic farming, soil health, climate change mitigation, sustainable agriculture

Introduction
Modern agricultural practices and the indiscriminate use of chemical inputs over the past four decades have led to the deterioration of natural ecosystems and soil health. These practices have contributed to several environmental and agricultural problems, including soil erosion, depletion of groundwater, soil salinity, pollution from fertilizers and pesticides, genetic erosion, reduced food quality, and Increased cultivation costs, ultimately making farmers economically vulnerable year after year. (Reddy *et al*., 2010) [23]. Several factors have contributed to the current crisis in agriculture, including the rapid Increase in the cost of industrially manufactured external inputs and the gradual withdrawal of government support in terms of investment and market intervention. Furthermore, the transition from traditional subsistence farming systems, which primarily relied on farm-derived inputs, to commercially oriented agriculture dependent on purchased inputs has intensified the vulnerability of farming systems. As a consequence, indigenous agricultural knowledge and local farming practices have largely been replaced by modern input-intensive technologies, leading to economically unviable and ecologically unsustainable farming enterprises (Hyvonen *et al*., 2003) [4].

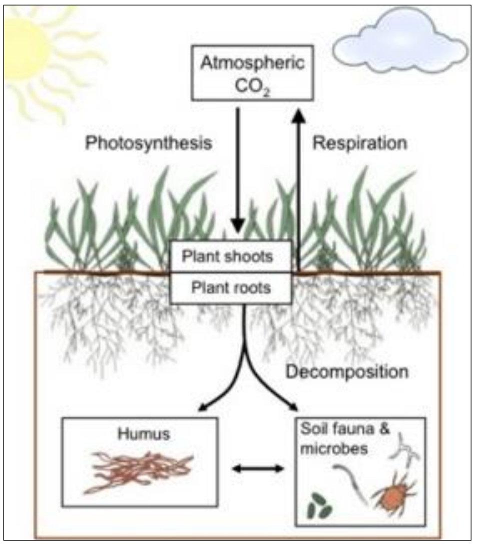
In this context, the development and adoption of alternative farming strategies have become essential for sustainable crop production. Organic farming has emerged as a promising approach and is gaining global acceptance due to its ecological, economic, and social advantages over conventional agricultural practices. Organic agriculture is a holistic production system that promotes and enhances natural biological processes while minimizing dependence on synthetic chemicals and genetically modified organisms. Studies have demonstrated that organic farming can ensure productivity, environmental sustainability, long-term soil health and soil carbon (Mäder *et al*., 2002; Seufert, *et al*., 2017) [14, 28].

Need for Sustainable Agricultural Practices

In this context, the development and adoption of alternative farming strategies have become essential for sustainable crop production. Organic farming has emerged as a promising approach and is gaining global acceptance due to its ecological, economic, and social advantages over conventional agricultural practices. Organic agriculture is a holistic production system that promotes and enhances natural biological processes while minimizing dependence on synthetic chemicals and genetically modified organisms. Studies have demonstrated that organic farming can ensure productivity, environmental sustainability, long-term soil health, and soil carbon sequestration (Mäder *et al*., 2002; Seufert *et al*., 2017) [14, 28]. Organic farming also improves biodiversity, enhances nutrient recycling, and promotes ecological balance within agricultural systems. The reduced use of synthetic fertilizers and pesticides minimizes environmental pollution and protects beneficial soil organisms. In addition, organic systems encourage the use of renewable farm resources and traditional knowledge for sustainable production. Therefore, organic farming is increasingly considered an environmentally sound and climate-resilient agricultural system suitable for long-term sustainability.

Concept of carbon sequestration

Carbon sequestration is a vital ecological process involving the capture and long-term storage of atmospheric carbon dioxide (CO_2) in terrestrial, oceanic, and geological reservoirs, thereby reducing greenhouse gas concentrations in the atmosphere. In agricultural ecosystems, carbon sequestration primarily occurs through photosynthetic fixation of atmospheric CO_2 into plant biomass and its subsequent incorporation into soil organic carbon (SOC) (Lal *et al*., 2004) [10]. Soil represents one of the largest terrestrial carbon pools and plays a significant role in regulating the global carbon cycle (Smith *et al*., 2008) [19]. The adoption of sustainable agricultural practices such as organic farming, conservation tillage, crop rotation, cover cropping, agroforestry, and the application of organic amendments enhances SOC accumulation and stabilizes carbon within the soil matrix. Increased SOC not only contributes to climate change mitigation but also improves soil physicochemical and biological properties, including soil structure, moisture retention, nutrient availability, and microbial activity (Paustian *et al*., 2016) [18]. Consequently, carbon sequestration has emerged as a key strategy for achieving sustainable agricultural productivity, environmental sustainability, and resilience against climate variability.



Mechanism of Soil Carbon Storage

Soil carbon sequestration mainly occurs through the addition of plant residues, root biomass, compost, and organic manures into the soil system. During decomposition, soil microorganisms convert these organic materials into stable humic substances that remain stored in soil for long periods. The stability of soil aggregates also plays an important role in protecting organic carbon from rapid decomposition and loss. Organic farming practices improve microbial biomass and enzymatic activity, thereby accelerating carbon transformation and stabilization processes (Six *et al*., 2002) [7]. Cover crops and reduced tillage further reduce soil disturbance and minimize carbon oxidation losses. Moreover, enhanced root growth under organic management contributes to greater below-ground carbon accumulation. Therefore, maintaining soil organic matter through organic farming practices is essential for improving soil fertility and increasing long-term carbon storage capacity.

Carbon sequestration under organic farming

According to Lal (2004) [10], enhancement of soil carbon stocks has a positive influence on crop productivity. An increase of one ton of carbon in the soil pool may improve crop yields by approximately 20–40 kg ha^{-1} in wheat and 10–20 kg ha^{-1} in maize. Owing to the high carbon retention capacity of soils, organic agriculture is increasingly recognized as an effective approach for climate change mitigation through atmospheric carbon sequestration. Organic farming practices contribute significantly to the buildup of soil organic matter, thereby improving soil moisture retention, alleviating soil acidity, and enhancing micronutrient availability. A study conducted in Japan during the period from 2012 to 2020 reported that soil organic carbon (SOC) content was comparatively higher under no-tillage systems than under conventional tillage practices. Over time, crop residues retained on the soil surface undergo decomposition and contribute organic matter to the soil, thereby enhancing soil fertility and carbon accumulation. The findings suggest that no-tillage practices play a significant role in improving soil carbon sequestration and maintaining soil health (RK Dewi *et al.*, 2021) [2]. The conventional farming practices result in a gradual decline in soil organic matter over time, whereas organic farming systems employing compost, farmyard manure, and other ecologically sustainable practices promote the accumulation of soil organic matter. Such practices create favorable soil conditions for crop growth and enhance long-term soil fertility through improved soil carbon sequestration Figure.

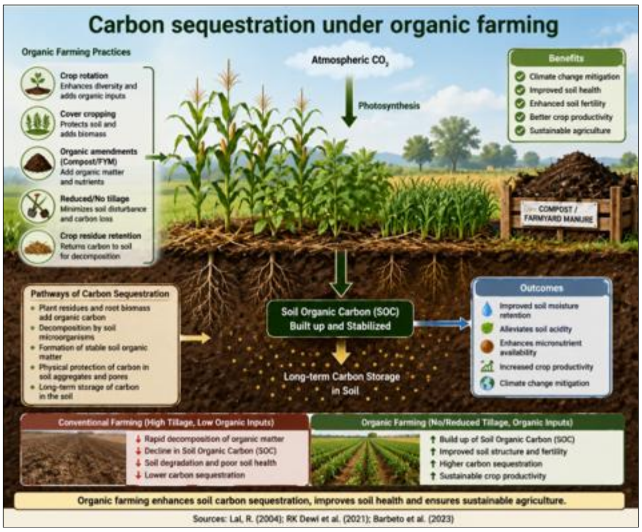


Fig 1: Carbon Sequestration and Soil Health Improvement under Organic Farming Practices

Role of Organic Amendments in Carbon Accumulation

Organic amendments such as compost, green manure, farmyard manure, crop residues, and vermicompost are major sources of carbon input into agricultural soils. These organic materials improve soil aggregation and provide energy sources for beneficial soil microorganisms. The decomposition of organic amendments leads to the formation of humus, which acts as a stable reservoir of soil organic carbon. Continuous addition of organic residues also improves nutrient cycling, moisture conservation, and soil aeration. Long-term application of organic manures has been reported to significantly increase SOC stocks compared to conventional fertilizer-based systems (Drinkwater *et al.*, 1998) [12]. In addition, organic amendments reduce nutrient losses through leaching and erosion, thereby improving nutrient use efficiency. Hence, the integration of organic inputs into farming systems is an important strategy for enhancing soil carbon sequestration and sustaining soil productivity.

Policy initiatives by GOI

Organic farming in India has received significant policy support through successive national development programmes and governmental initiatives (Reddy *et al.*, 2010) [23]. The Tenth Five-Year Plan and the Ninth Five-Year Plan emphasized the cultivation and promotion of organic produce in plantation crops, spices, and condiments through the use of organic and biological inputs to enhance environmental conservation and ensure agricultural sustainability (Roychowdhury *et al.*, 2013) [20]. The Government of India introduced the National Programme for Organic Production (NPOP) in 2001, aimed at establishing standards for organic production, accreditation, certification, and marketing of organic products. In 2003, the Government of India established the National Institute of Organic Farming with the primary objective of developing standards, regulations, and certification systems for organic products in accordance with international norms (Wani SA *et al.*, 2017) [36]. The government launched many programmes like Paramparagat Krishi Vikas Yojana (PKVY), One District-One Product (ODOP), Mission Organic Value Chain Development for North Eastern Region (MOVCDNER), National Food Security Mission (NFSM) etc.

Impact of Organic Farming on Soil Health

Physical Properties

The physical properties of soil denote structure, texture, bulk density, porosity, water-holding capacity, and infiltration characteristics. Crop rotation is an integral component of organic farming that directly and indirectly influences the physical structure of soil (Chandra *et al.*, 2008) [9]. Mulching the soil surface with organic materials helps maintain the soil in a soft, friable, and moist condition, thereby creating a favourable environment for beneficial microorganisms and improving soil bulk density and porosity (Jannoura *et al.*, 2014) [6]. The decomposition of organic residues adds organic matter to the soil, which helps regulate the soil hydrological response, enhances water retention, and improves infiltration characteristics (Humberto BC *et al.*, 2023) [3]. Application of organic fertilizers not only supplies nutrients to the current crop but also contributes residual nutrients that benefit succeeding crops (Papadopoulos *et al.*, 2014) [5]. Organic farming practices also reduce soil erosion, improve aggregate stability, and enhance root penetration. These improvements in physical properties contribute significantly to sustainable crop production and long-term soil fertility maintenance.

Chemical Properties

The chemical properties of soil involve pH, EC, CEC, AEC, soil organic matter, and nutrient availability. The incorporation of organic amendments such as farmyard manure (FYM), vermicompost, and green manures increases soil organic carbon (SOC) content, which plays a vital role in improving cation exchange capacity, nutrient availability, microbial activity, soil structure, and moisture retention (Stozle *et al.*, 2000). Organically cultivated soils generally exhibit higher carbon stocks, greater carbon sequestration rates, and improved nitrogen dynamics compared to conventional methods (Reganald *et al.*, 1987). Organic farming also enhances the availability of micronutrients and reduces nutrient losses through leaching. The gradual decomposition of organic inputs ensures a steady release of nutrients to plants over time. In addition, reduced dependence on synthetic fertilizers helps minimize soil acidity and salinity problems. Therefore, organic farming contributes to balanced nutrient cycling and improved soil chemical fertility.

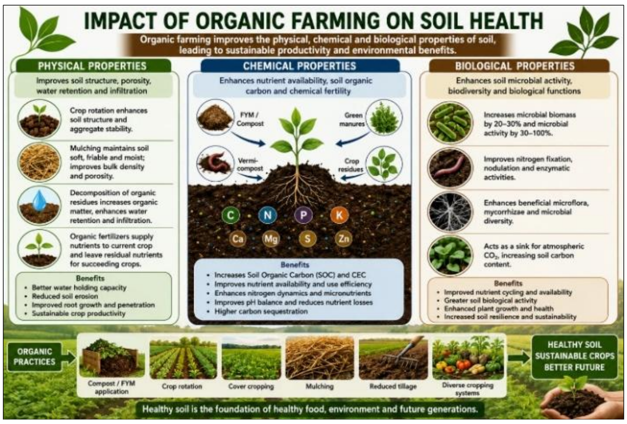


Fig 2: Impact of Organic Farming on Physical, Chemical, and Biological Properties of Soil Heal`th

Biological Properties

Organic farming has been reported to enhance microbial biomass by 20–30% and microbial activity by 30–100% compared to conventional systems (Mader *et al*., 2000) [13]. Higher soil organic matter content under organic management promotes greater microbial activity, improves the soil nitrogen-supplying capacity, and acts as an important sink for atmospheric CO_2, thereby increasing soil carbon content (Smith *et al*., 1997) [19]. Organic fertilizers improve nodulation, photosynthetic efficiency, nitrogen fixation, enzymatic activity, and nutrient accumulation in crops (Lal *et al*., 1988) [11]. The application of organic amendments such as vermicompost, farmyard manure, sewage sludge, municipal waste, and cattle manure enhances soil microbial biomass and stimulates beneficial soil microflora (Yadav *et al*., 2013) [26]. These organic inputs improve microbial diversity and support the proliferation of heterotrophic bacterial populations, thereby strengthening soil biological activity (Sudarsan *et al*., 2014) [32]. Increased earthworm activity and beneficial microbial populations under organic farming also improve decomposition and nutrient mineralization processes. Consequently, organic farming enhances overall soil biological health and ecosystem sustainability.

Table 1: Influence of Organic Farming on soil health

Management Practice	Physical Parameters	Chemical Parameters	Biological Parameters
Organic Amendments (Compost/Manure)	Decrease Bulk Density; Increase Macroporosity and Aggregate Stability	Increase Soil Organic Carbon (SOC); Increase CEC and Labile Phosphorus	Increase Microbial Biomass Carbon (MBC) and Dehydrogenase Activity
Cover Cropping	Increase Infiltration Rate; Decrease Surface Crust Formation	Increase Total Nitrogen (TN); Decrease Nitrate Leaching	Increase Mycorrhizal Colonization and Root Exudate Diversity
Conservation Tillage	Increase Mean Weight Diameter (MWD) of Aggregates	Increase Stratified Organic Matter and Carbon Sequestration	Increase Earthworm Density and Fungal: Bacterial Ratios
Diversified Rotations	Decrease Soil Penetration Resistance	Increase Nutrient Use Efficiency (NUE); Balanced pH	Increase Functional Diversity and Suppress Pathogen activity.
Green Manuring	Increase Volumetric Water Content (VWC)	Increase Mineralizable Nitrogen and Trace Element Availability	Increase Soil Respiration Rates and Phosphatase Activity

Conclusion

Organic farming plays a significant role in improving soil health and enhancing carbon sequestration through the accumulation of soil organic carbon (SOC). The continuous application of organic amendments, crop rotation, residue retention, and reduced tillage practices contributes to improved physical, chemical, and biological properties of soil. Increased SOC enhances nutrient availability, microbial activity, soil structure, and water-holding capacity, thereby supporting sustainable crop productivity. Organic farming systems also act as an effective sink for atmospheric CO_2 and contribute to climate change mitigation. Several studies have reported higher carbon stocks, greater microbial biomass, and improved soil fertility under organic management compared to conventional farming systems. Furthermore, policy initiatives by the Government of India have promoted the adoption of organic agriculture for sustainable agricultural development. Therefore, organic farming can be considered an ecologically sustainable and economically viable approach for maintaining soil quality, enhancing carbon sequestration, and ensuring long-term agricultural sustainability

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