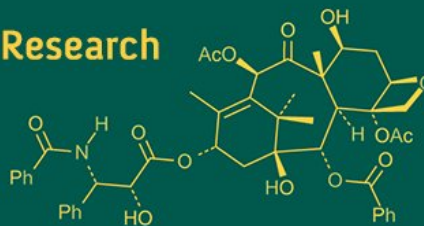


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Dr. Asim Chandra Dash
Assistant Professor,
Department of Agronomy,
College of Agriculture,
Odisha University of
Agriculture and Technology,
Bhubaneswar, Odisha, India

Dr. Gyanaranjan Sahoo
Scientist (Forestry), Krishi
Vigyan Kendra, Odisha
University of Agriculture and
Technology, Nayagarh,
Odisha, India

Dr. Akshaya Kumar Sethy
Scientist (Agronomy), All
India Coordinated Research
Project on Groundnut, Odisha
University of Agriculture and
Technology, Bhubaneswar,
Odisha, India

Dr. Suchismita Tripathy
Associate Professor,
Department of Agronomy,
College of Agriculture, Odisha
University of Agriculture and
Technology, Bhubaneswar,
Odisha, India

Corresponding Author:
Dr. Gyanaranjan Sahoo
Scientist (Forestry), Krishi
Vigyan Kendra, Odisha
University of Agriculture and
Technology, Nayagarh,
Odisha, India

Regenerative agriculture and soil carbon sequestration for climate-resilient and sustainable farming

Asim Chandra Dash, Gyanaranjan Sahoo, Akshaya Kumar Sethy and Suchismita Tripathy

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Abstract

Soil carbon sequestration has gained significant attention as a scientifically robust and economically viable approach to addressing the dual challenges of climate change mitigation and sustainable agricultural development. Agricultural soils represent one of the largest terrestrial carbon reservoirs, and their management plays a decisive role in regulating atmospheric carbon dioxide (CO₂) concentrations. However, decades of intensive farming practices such as excessive tillage, monoculture systems, and overreliance on synthetic inputs—have substantially depleted soil organic carbon (SOC) stocks, thereby reducing soil fertility and increasing greenhouse gas emissions, regenerative agriculture has emerged as a transformative framework that prioritizes the restoration of soil health, enhancement of biodiversity, and re-establishment of ecological processes. This article critically examines the mechanisms and potential of soil carbon sequestration within regenerative agricultural systems. It elucidates the biological and physicochemical processes through which carbon is captured from the atmosphere via plant photosynthesis and subsequently stabilized in soil organic matter fractions. The study further explores key regenerative practices including conservation tillage, cover cropping, crop diversification, agroforestry, and organic amendments and their synergistic role in enhancing carbon storage, improving soil structure, and promoting microbial activity, the article highlights the contribution of increased SOC to climate-resilient farming. Carbon-rich soils exhibit improved water retention, nutrient availability, and structural stability, enabling agricultural systems to better withstand climatic stresses such as droughts, floods, and temperature variability. These attributes are particularly critical in the context of smallholder farming systems, where resilience to climate shocks is directly linked to food security and livelihoods, the implementation of soil carbon sequestration at scale faces several constraints, including challenges in accurate measurement and monitoring of SOC, delayed realization of benefits, financial limitations during the transition phase, and insufficient policy support. The article therefore underscores the need for integrated policy frameworks, incentive mechanisms such as carbon credit systems, and enhanced research and extension services to facilitate adoption, soil carbon sequestration through regenerative agriculture represents a holistic and scalable pathway toward climate-resilient farming systems. By aligning agricultural productivity with environmental sustainability, it offers a strategic solution to global challenges related to food security, land degradation, and climate change.

Keywords: Soil carbon sequestration, regenerative agriculture, soil organic carbon (SOC), climate change mitigation, climate-resilient farming, sustainable agriculture

Introduction

Agriculture occupies a central position in the global climate system, functioning simultaneously as a source of greenhouse gas emissions and a potential sink for atmospheric carbon dioxide (CO₂). Contemporary agricultural practices, particularly those associated with industrial intensification, have significantly altered natural biogeochemical cycles. Extensive tillage, monoculture-based cropping systems, and the heavy application of synthetic fertilizers and pesticides have contributed to the depletion of soil organic carbon (SOC), soil erosion, and declining fertility. These processes not only undermine long-term agricultural productivity but also exacerbate climate change through increased emissions of CO₂, methane (CH₄), and nitrous oxide (N₂O) [1]. Soils represent one of the largest carbon reservoirs in the terrestrial biosphere, storing more carbon than the atmosphere and

vegetation combined. This highlights their critical role in climate regulation and underscores the importance of sustainable soil management. Soil carbon sequestration, defined as the process of capturing atmospheric CO₂ and storing it in soil organic matter, has emerged as a promising strategy to offset greenhouse gas emissions while simultaneously improving soil quality ^[2]. The enhancement of SOC is particularly significant because it directly influences soil structure, nutrient cycling, water retention capacity, and biological activity. In recent years, regenerative agriculture has gained prominence as a holistic and adaptive approach to land management that prioritizes ecological restoration and long-term sustainability. Unlike conventional systems that often focus on maximizing short-term yields, regenerative agriculture emphasizes the regeneration of soil health, the enhancement of biodiversity, and the restoration of ecosystem functions ^[3]. It integrates a suite of practices such as reduced or zero tillage, cover cropping, crop diversification, agroforestry, and the incorporation of organic amendments that collectively contribute to increased carbon sequestration and improved resilience of farming systems. The growing interest in regenerative agriculture is closely linked to the increasing frequency and intensity of climate-related stresses, including droughts, floods, heatwaves, and erratic precipitation patterns. These challenges threaten global food security and disproportionately affect

smallholder farmers, particularly in developing regions. Climate-resilient farming systems, therefore, are essential for ensuring stable agricultural production under changing environmental conditions. By enhancing SOC and improving soil health, regenerative practices strengthen the capacity of agricultural systems to absorb, adapt to, and recover from climatic shocks. Furthermore, the concept of carbon farming—where agricultural practices are deliberately designed to capture and store carbon—has gained traction in both scientific and policy domains. International initiatives and climate agreements increasingly recognize the role of soils in achieving carbon neutrality targets. However, despite its potential, the adoption of soil carbon sequestration practices remains limited due to technical, economic, and institutional barriers ^[4]. These include difficulties in measuring and verifying SOC changes, lack of financial incentives, and insufficient awareness among farmers, a comprehensive understanding of the relationship between soil carbon sequestration and regenerative agriculture is essential. This article aims to explore the underlying mechanisms, evaluate the benefits for climate-resilient farming, and identify the challenges and opportunities associated with large-scale implementation. By integrating scientific insights with practical considerations, it seeks to provide a pathway toward sustainable and climate-smart agricultural systems.

Table 1: Key Regenerative Agricultural Practices and Their Effects on Soil Carbon Sequestration

Practice	Description	Impact on Soil Carbon Sequestration	Additional Benefits
Reduced/No Tillage	Minimizes soil disturbance	Decreases carbon loss, enhances SOC	Improves soil structure, reduces erosion
Cover Cropping	Growing crops during fallow periods	Increases biomass input to soil	Weed suppression, moisture conservation
Crop Rotation	Alternating crops across seasons	Enhances carbon input diversity	Breaks pest cycles, improves soil fertility
Agroforestry	Integration of trees with crops/livestock	Increases long-term carbon storage	Microclimate regulation, biodiversity
Organic Amendments	Application of compost/manure	Adds stable organic carbon	Improves nutrient availability
Integrated Livestock	Managed grazing systems	Enhances nutrient cycling	Promotes root growth, improves soil biology

Table 2: Soil Carbon Pools and Their Characteristics

Carbon Pool	Composition	Turnover Time	Role in Soil System
Active (Labile)	Fresh residues, microbial biomass	Days to years	Nutrient cycling, microbial activity
Slow	Partially decomposed organic matter	Decades	Soil aggregation, intermediate storage
Passive (Stable)	Humus, resistant compounds	Centuries-millennia	Long-term carbon storage, climate mitigation

Table 3: Benefits of Soil Carbon Sequestration

Category	Specific Benefit	Description
Environmental	Climate change mitigation	Reduces atmospheric CO ₂ levels
Soil Health	Improved structure	Enhances aggregation and aeration
Water Management	Increased water retention	Reduces drought stress and runoff
Agricultural	Enhanced productivity	Supports stable and higher crop yields
Biodiversity	Increased biological activity	Promotes microbial and faunal diversity
Economic	Reduced input costs	Lowers dependence on synthetic fertilizers
Climate Resilience	Improved stress tolerance	Enhances resistance to extreme weather conditions

2. Concept of Soil Carbon Sequestration

Soil carbon sequestration refers to the long-term storage of carbon in soil systems through biological, chemical, and physical processes that transfer atmospheric carbon dioxide (CO₂) into stable soil carbon pools. This process is primarily driven by plant photosynthesis, wherein atmospheric CO₂ is assimilated into plant biomass and subsequently transferred

to the soil through root exudates, litter deposition, and residue incorporation. The efficiency of this process depends on climatic conditions, soil type, land management practices, and ecosystem dynamics ^[5]. Soil carbon exists in multiple pools that differ in stability and turnover rates:

- **Active (labile) carbon pool:** This fraction includes

fresh plant residues and microbial biomass with rapid decomposition rates, typically cycling within days to a few years. Although short-lived, it plays a critical role in nutrient availability and soil microbial activity.

- **Slow carbon pool:** Comprising partially decomposed organic matter, this pool has intermediate stability, with turnover times ranging from decades. It contributes significantly to soil aggregation and structural stability.
- **Passive (stable) carbon pool:** This includes highly decomposed organic compounds such as humus, which can persist in soils for centuries or even millennia. This pool is crucial for long-term carbon storage and climate mitigation.

The stabilization of carbon in soil occurs through several mechanisms:

1. **Biochemical stabilization:** Transformation of organic materials into resistant compounds such as humic substances through microbial decomposition.
2. **Physical protection:** Encapsulation of organic matter within soil aggregates, protecting it from microbial degradation.
3. **Chemical stabilization:** Interaction of organic carbon with mineral surfaces, particularly clay and silt particles, forming organo-mineral complexes.

The rate of soil carbon sequestration is influenced by both natural and anthropogenic factors. Climate variables such as temperature and precipitation regulate plant productivity and microbial decomposition rates. Soil properties including texture, mineralogy, and pH affect carbon retention capacity. Importantly, land-use and management practices determine whether soils function as carbon sinks or sources. From a global perspective, soils have the potential to sequester significant quantities of carbon annually, thereby offsetting a portion of anthropogenic emissions^[6]. However, sequestration is not indefinite; soils reach a saturation point beyond which additional carbon storage becomes limited. Therefore, maintaining and protecting existing SOC stocks is as important as enhancing them. Measurement and monitoring of soil carbon remain complex due to spatial variability and methodological constraints. Techniques range from traditional laboratory-based analyses to advanced remote sensing and modeling approaches. Accurate quantification is essential for integrating soil carbon sequestration into climate mitigation frameworks, including carbon trading and sustainability assessments.

3. Principles of Regenerative Agriculture

Regenerative agriculture is a systems-based approach that seeks to restore and enhance the ecological integrity of agricultural landscapes while maintaining productive capacity. It is grounded in the understanding that soil is a living system, and its health is fundamental to sustainable food production. Unlike conventional approaches that often prioritize short-term yield maximization, regenerative agriculture focuses on long-term resilience, resource efficiency, and ecosystem functionality^[7].

The core principles of regenerative agriculture are interrelated and operate synergistically:

3.1 Minimization of Soil Disturbance

Reducing mechanical disturbance through no-till or minimum tillage practices helps preserve soil structure,

prevent the breakdown of aggregates, and reduce oxidation of soil organic matter^[8]. This leads to lower carbon losses and improved habitat conditions for soil microorganisms. Additionally, reduced disturbance minimizes erosion and enhances water infiltration.

3.2 Continuous Soil Cover

Maintaining permanent soil cover through cover crops, crop residues, or mulching protects the soil surface from erosion, temperature fluctuations, and moisture loss. Cover crops also contribute organic matter, enhance soil structure, and suppress weeds^[9]. This continuous input of biomass is essential for sustaining soil carbon levels.

3.3 Crop Diversification

Diverse cropping systems, including crop rotation, intercropping, and polycultures, improve ecological balance and resource utilization. Different plant species contribute varying root architectures and biochemical compounds, which support diverse microbial communities and enhance nutrient cycling^[10]. Crop diversity also reduces pest and disease pressures, decreasing reliance on chemical inputs.

3.4 Integration of Livestock

Incorporating livestock into cropping systems facilitates nutrient recycling and promotes soil fertility^[11]. Managed grazing systems, such as rotational or holistic grazing, stimulate plant growth and root development, increasing carbon inputs into the soil. Animal manure further contributes to organic matter and microbial activity.

3.5 Enhancement of Biodiversity

Regenerative agriculture emphasizes both above-ground and below-ground biodiversity. A diverse ecosystem improves resilience against environmental stresses and supports essential ecosystem services such as pollination, pest regulation, and nutrient cycling^[12]. Soil microbial diversity, in particular, plays a crucial role in carbon stabilization and nutrient transformation.

3.6 Use of Organic Amendments

Application of compost, manure, and other organic inputs enriches soil organic matter and enhances biological activity^[13]. These amendments improve soil structure, increase water-holding capacity, and provide a slow-release source of nutrients, reducing dependence on synthetic fertilizers.

3.7 Context-Specific Management

Regenerative practices are not universally uniform; they must be adapted to local environmental conditions, including climate, soil type, and socio-economic context. This flexibility allows farmers to design site-specific strategies that optimize both productivity and sustainability, these principles aim to create a self-sustaining agricultural system that mimics natural ecosystems. By enhancing soil organic carbon, improving water dynamics, and fostering biodiversity, regenerative agriculture contributes directly to climate change mitigation and adaptation^[14]. Its holistic nature also aligns with broader sustainability goals, including food security, environmental conservation, and rural livelihood improvement, regenerative agriculture provides a practical and scalable framework for implementing soil carbon sequestration strategies, making it a cornerstone of climate-resilient farming systems

4. Mechanisms Linking Regenerative Practices to Carbon Sequestration

The relationship between regenerative agricultural practices and soil carbon sequestration is governed by a set of interconnected biological and physicochemical mechanisms that regulate carbon inputs, transformation, and stabilization within the soil system. These mechanisms are not isolated; rather, they operate synergistically to enhance the capacity of soils to function as long-term carbon sinks. A fundamental mechanism involves the increase in plant-derived carbon inputs. Regenerative practices such as cover cropping, crop diversification, and agroforestry enhance overall biomass production, both above and below ground. Through photosynthesis, plants assimilate atmospheric carbon dioxide (CO₂) and allocate a substantial portion of this carbon to root systems. Root exudates—comprising sugars, amino acids, and organic acids—serve as substrates for soil microorganisms, thereby stimulating microbial activity and promoting the formation of soil organic matter (SOM). Compared to above-ground residues, root-derived carbon is often more efficiently stabilized in soil, making it a critical component of long-term sequestration. Another key mechanism is the reduction of carbon losses through minimized soil disturbance^[15]. Conventional tillage disrupts soil aggregates and exposes previously protected organic matter to microbial decomposition, resulting in rapid oxidation and release of CO₂. In contrast, no-till or reduced tillage systems preserve soil structure and maintain the physical protection of organic matter within aggregates. This enhances the retention of carbon and reduces its turnover rate, contributing to the accumulation of stable soil organic carbon (SOC) over time.

The enhancement of soil aggregation plays a central role in carbon stabilization. Soil aggregates, formed through interactions among mineral particles, organic matter, and microbial by-products, create microenvironments that physically protect organic carbon from decomposition. Regenerative practices that promote root growth and microbial activity—such as organic amendments and diversified cropping systems—facilitate the formation and stabilization of these aggregates. As a result, carbon becomes occluded within soil structures, increasing its resistance to microbial breakdown. Microbial processes are also fundamental to the sequestration pathway. Regenerative systems support a diverse and active soil microbial community, including bacteria, fungi, and actinomycetes, which drive the decomposition and transformation of organic materials^[16]. Microbial residues, particularly necromass, contribute significantly to the formation of stable carbon fractions. Symbiotic associations such as mycorrhizal fungi further enhance carbon transfer from plants to soil and improve nutrient uptake, reinforcing the overall efficiency of the system, chemical interactions between organic carbon and soil minerals contribute to long-term stabilization. Fine-textured soils rich in clay and silt particles have a greater capacity to adsorb organic compounds, forming organo-mineral complexes that protect carbon from decomposition. Regenerative practices that increase organic inputs enhance these interactions, thereby improving the persistence of carbon in soil. Water dynamics also influence carbon sequestration mechanisms. Improved soil structure and increased organic matter enhance water infiltration and retention, creating favorable conditions for plant growth and microbial activity. At the same time, balanced moisture

levels reduce the likelihood of extreme aerobic or anaerobic conditions that could accelerate carbon loss through decomposition or methane emissions, regenerative agriculture modifies the soil environment in ways that increase carbon inputs, reduce losses, and enhance stabilization processes^[16-17]. The cumulative effect of these mechanisms is a gradual but sustained increase in soil carbon stocks, contributing to both climate change mitigation and improved soil functionality.

5. Benefits of Soil Carbon Sequestration

Soil carbon sequestration offers a wide range of environmental, agronomic, and socio-economic benefits, making it a cornerstone of sustainable and climate-resilient agricultural systems. These benefits extend beyond carbon storage, influencing multiple dimensions of ecosystem health and agricultural productivity. One of the most significant benefits is its contribution to climate change mitigation^[18]. By capturing atmospheric carbon dioxide (CO₂) and storing it in stable soil forms, soil carbon sequestration directly reduces the concentration of greenhouse gases in the atmosphere. Although the sequestration potential varies across regions and management systems, even modest increases in soil organic carbon (SOC) at a global scale can offset a substantial portion of anthropogenic emissions. This positions agricultural soils as an important component of climate mitigation strategies.

Improved soil health and fertility represent another major advantage. Soil organic carbon is a key determinant of soil quality, influencing its physical, chemical, and biological properties. Higher SOC levels enhance soil structure by promoting aggregation, which improves aeration and root penetration^[19]. Chemically, organic matter acts as a reservoir of essential nutrients such as nitrogen, phosphorus, and sulfur, releasing them gradually through microbial decomposition. Biologically, it supports a diverse and active microbial community that drives nutrient cycling and suppresses soil-borne diseases.

Soil carbon sequestration also plays a crucial role in water management. Carbon-rich soils exhibit greater porosity and water-holding capacity, enabling them to retain moisture for longer periods. This is particularly beneficial in regions prone to drought, where improved water retention can sustain crop growth during dry spells. At the same time, enhanced infiltration reduces surface runoff and the risk of flooding, thereby improving overall water-use efficiency. From a productivity perspective, increased SOC contributes to stable and enhanced crop yields^[20]. Healthy soils provide a favorable environment for root development, nutrient uptake, and plant growth. Over time, this leads to more consistent yields and reduced dependence on synthetic fertilizers and irrigation inputs. Such improvements are especially important for smallholder farmers, whose livelihoods are closely tied to soil productivity. Biodiversity conservation is another critical benefit. Regenerative practices associated with soil carbon sequestration foster diverse ecosystems, both above and below ground. Soil microorganisms, insects, and other organisms play essential roles in maintaining ecosystem functions, including decomposition, nutrient cycling, and pest regulation. Enhanced biodiversity increases the resilience of agricultural systems to environmental stresses and disturbances, environmental and agronomic gains, soil

carbon sequestration offers economic and social benefits. Reduced input costs, improved yield stability, and potential participation in carbon credit markets can enhance farm profitability^[21-22]. Furthermore, sustainable soil management contributes to long-term land productivity, supporting food security and rural livelihoods, soil carbon sequestration strengthens climate resilience by improving the adaptive capacity of agricultural systems. Soils with higher organic carbon content are better equipped to withstand extreme weather events, such as droughts and heavy rainfall, due to their improved structural stability and water regulation properties. This resilience is increasingly important in the face of climate variability and uncertainty, soil carbon sequestration provides a multifaceted set of benefits that integrate environmental sustainability with agricultural productivity and economic viability. Its role in supporting resilient farming systems underscores its importance as a key strategy for addressing global challenges related to climate change, land degradation, and food security.

6. Role in Climate-Resilient Farming

Soil carbon sequestration plays a foundational role in enhancing the resilience of agricultural systems to climate variability and extreme weather events. Climate-resilient farming refers to the capacity of agricultural systems to maintain productivity, adapt to changing climatic conditions, and recover from disturbances such as droughts, floods, and temperature extremes. The accumulation of soil organic carbon (SOC) directly strengthens these adaptive and buffering capacities through multiple interrelated pathways. One of the primary contributions of SOC to climate resilience lies in its effect on soil physical properties. Increased organic carbon improves soil aggregation, which enhances structural stability and reduces susceptibility to erosion caused by wind and water. Well-aggregated soils exhibit higher porosity, allowing for efficient water infiltration and reduced surface runoff. This is particularly important during heavy rainfall events, where improved infiltration mitigates flooding and soil loss. Conversely, during dry periods, the enhanced structure supports deeper root penetration, enabling crops to access moisture from deeper soil layers. Another critical aspect is water regulation and drought mitigation. Soils rich in organic carbon have a greater capacity to retain water due to the hygroscopic nature of organic matter. This increased water-holding capacity ensures a more consistent supply of moisture to plants, even under conditions of irregular rainfall^[23]. As a result, crops grown in carbon-rich soils are less vulnerable to drought stress, leading to more stable yields. This buffering effect is especially significant in arid and semi-arid regions, where water availability is a limiting factor for agricultural productivity.

Soil carbon also contributes to nutrient stability and cycling under stress conditions. Organic matter acts as a reservoir of essential nutrients, releasing them gradually through microbial decomposition. During periods of climatic stress, when nutrient uptake may be constrained, this slow-release mechanism ensures a sustained supply of nutrients to crops. Additionally, improved microbial activity enhances nutrient transformation processes, further supporting plant growth under adverse conditions. The role of SOC in temperature regulation is another important dimension of climate resilience. Organic matter can moderate soil temperature

fluctuations by improving thermal buffering capacity. This creates a more stable microenvironment for root development and microbial activity, reducing the negative impacts of extreme heat or cold on plant growth, regenerative systems that enhance soil carbon often promote diverse and integrated farming practices, such as agroforestry and mixed cropping^[24]. These systems increase overall system resilience by distributing risk across multiple crops and components. Biodiversity within these systems contributes to ecological stability, reducing vulnerability to pests, diseases, and climatic shocks, soil carbon sequestration supports the adaptive capacity of farmers by improving long-term soil productivity and reducing dependence on external inputs. Farmers operating within regenerative systems are better positioned to respond to climatic uncertainties, as their soils are inherently more robust and self-sustaining. This adaptability is crucial for ensuring food security in the face of ongoing climate change, soil carbon sequestration enhances climate resilience by improving soil structure, water dynamics, nutrient availability, and ecosystem stability. These improvements collectively enable agricultural systems to withstand and recover from climatic stresses, making SOC a central component of sustainable and resilient farming strategies.

7. Challenges and Limitations

Despite the substantial potential of soil carbon sequestration and regenerative agriculture, several challenges and limitations hinder their widespread adoption and effective implementation. These constraints span scientific, economic, technical, and institutional dimensions, and must be addressed to realize the full benefits of these approaches. One of the primary challenges is the difficulty in measuring and verifying changes in soil organic carbon (SOC). Soil carbon levels exhibit high spatial and temporal variability, influenced by factors such as soil type, climate, and management history. Accurate quantification requires repeated sampling, standardized methodologies, and long-term monitoring, all of which can be resource-intensive^[25]. This complexity poses a significant barrier to the integration of soil carbon sequestration into carbon markets and policy frameworks, where reliable measurement and verification are essential.

Another limitation is the time lag associated with carbon sequestration benefits. Unlike immediate yield responses to conventional inputs, increases in SOC occur gradually over years or even decades. This delayed realization of benefits may discourage farmers, particularly those with limited financial resources or short-term planning horizons. The slow rate of carbon accumulation also means that sustained management efforts are required to maintain and enhance SOC levels. Economic constraints represent a major barrier to adoption. Transitioning from conventional to regenerative practices often involves initial costs, including investments in new equipment, seeds for cover crops, and training. Additionally, there may be short-term yield reductions during the transition period as the system adjusts^[26]. Without adequate financial support or incentives, farmers may be reluctant to adopt these practices despite their long-term advantages. There are also knowledge and capacity gaps among farmers and agricultural stakeholders. Regenerative agriculture requires a systems-based understanding of soil-plant interactions and ecosystem

dynamics, which may not be widely accessible. Limited access to extension services, training programs, and technical guidance further constrains the adoption of these practices, particularly in developing regions. Policy and institutional barriers further complicate implementation. In many regions, agricultural policies continue to favor conventional practices through subsidies and support mechanisms that do not account for environmental sustainability. The absence of clear policy frameworks for carbon farming, along with limited integration of soil carbon strategies into national climate action plans, restricts the scaling of regenerative approaches. Environmental and biophysical constraints must also be considered. The potential for carbon sequestration varies across different soil types and climatic conditions, with some regions having limited to store additional carbon. Moreover, soils can reach

a saturation point beyond which further sequestration becomes minimal. There is also the risk of carbon reversal, where stored carbon is released back into the atmosphere due to changes in land use or management practices, socio-economic factors, including land tenure insecurity, market access, and cultural practices, influence the adoption of regenerative agriculture ^[27]. Farmers may be hesitant to invest in long-term soil health improvements if they lack secure land rights or access to markets that reward sustainable practices. Addressing these challenges requires coordinated efforts involving research, policy reform, financial incentives, and capacity building. Overcoming these barriers is essential for scaling soil carbon sequestration as a viable climate mitigation and adaptation strategy.

Table 4: Challenges and Possible Solutions in Soil Carbon Sequestration

Challenge	Description	Potential Solution
Measurement difficulty	High variability in SOC estimation	Develop standardized protocols, digital monitoring
Time lag in benefits	Slow accumulation of SOC	Provide transitional incentives
Economic constraints	High initial investment	Subsidies, carbon credits, financial support
Knowledge gaps	Limited awareness among farmers	Extension services, training programs
Policy limitations	Lack of supportive frameworks	Integrate into climate and agricultural policies
Carbon saturation	Limited storage capacity over time	Focus on maintenance and sustainable practices

Table 5: Role of Soil Carbon in Climate-Resilient Farming

Factor	Influence of Soil Carbon	Outcome for Farming Systems
Soil Structure	Improved aggregation	Reduced erosion, better root growth
Water Retention	Higher moisture-holding capacity	Drought resilience
Nutrient Availability	Gradual nutrient release	Stable crop productivity
Temperature Buffering	Moderation of soil temperature	Protection against extreme heat/cold
Biodiversity	Enhanced microbial and faunal diversity	

8. Policy and Implementation Strategies

The successful promotion and large-scale adoption of soil carbon sequestration through regenerative agriculture depend on the development of supportive policy frameworks and effective implementation strategies. These strategies must integrate scientific knowledge, economic incentives, institutional support, and stakeholder engagement to create an enabling environment for sustainable land management. A key policy approach involves the establishment of incentive-based mechanisms that reward farmers for adopting practices that enhance soil carbon. Carbon credit systems and payment for ecosystem services (PES) schemes can provide financial compensation for carbon sequestration and other environmental benefits ^[28]. By assigning economic value to ecosystem services, these mechanisms encourage farmers to transition toward regenerative practices. However, their effectiveness depends on robust systems for measuring, reporting, and verifying SOC changes. Integration of soil carbon sequestration into national and international climate policies is another critical strategy. Including agricultural soils in climate action plans, such as Nationally Determined Contributions (NDCs), can elevate their importance in mitigation efforts. This integration ensures alignment between agricultural development goals and climate objectives, facilitating coordinated action across sectors.

Investment in research and technological innovation is essential for advancing soil carbon sequestration. Developing cost-effective and accurate methods for monitoring SOC, including remote sensing technologies,

digital soil mapping, and modeling tools, can improve data reliability and accessibility. Research should also focus on region-specific best practices, enabling the adaptation of regenerative approaches to diverse agroecological conditions. Strengthening agricultural extension services and capacity building is crucial for bridging knowledge gaps ^[29]. Training programs, demonstration farms, and farmer-to-farmer knowledge exchange platforms can enhance awareness and technical expertise. Empowering farmers with practical knowledge enables them to implement regenerative practices effectively and adapt them to local conditions.

Public-private partnerships (PPPs) can play a significant role in scaling regenerative agriculture. Collaboration among governments, research institutions, non-governmental organizations, and private sector actors can facilitate resource mobilization, technology transfer, and market development. For example, private companies can support sustainable supply chains by incentivizing farmers to adopt soil-friendly practices. Another important strategy is the reorientation of agricultural subsidies and support systems. Redirecting subsidies from input-intensive practices toward sustainable land management can encourage the adoption of regenerative agriculture. Policies that support crop diversification, organic inputs, and conservation practices can create a more favorable economic environment for soil carbon sequestration. Ensuring land tenure security and inclusive governance is also vital. Farmers are more likely to invest in long-term soil health improvements when they have secure rights to their

land. Inclusive policies that consider the needs of smallholder farmers, women, and marginalized communities can enhance participation and equity in the transition toward regenerative systems^[30]. Finally, the development of market linkages and certification systems for sustainably produced agricultural products can provide additional incentives. Certification schemes that recognize regenerative practices can create premium markets, rewarding farmers for environmental stewardship, effective policy and implementation strategies must adopt a holistic and multi-level approach. By combining economic incentives, institutional support, technological innovation, and stakeholder engagement, it is possible to scale soil carbon sequestration and regenerative agriculture as integral components of climate-resilient farming systems.

9. Future Perspectives

The future of soil carbon sequestration and regenerative agriculture is closely linked to advancements in science, technology, and policy integration, as well as increasing global recognition of the role of soils in climate regulation. As the urgency to address climate change intensifies, these approaches are expected to become central components of sustainable agricultural transformation^[30]. One of the most promising areas of development lies in technological innovation for soil carbon measurement and monitoring. Emerging tools such as remote sensing, geographic information systems (GIS), digital soil mapping, and machine learning models are enhancing the precision and scalability of soil carbon assessments. These technologies enable real-time monitoring and facilitate the development of reliable carbon accounting systems, which are essential for participation in carbon markets and climate finance mechanisms. Improved data accuracy will also strengthen scientific understanding of carbon dynamics across diverse agroecosystems. Another important direction is the advancement of climate-smart and region-specific agricultural practices. Future research is likely to focus on tailoring regenerative strategies to specific agroecological zones, considering variations in climate, soil type, cropping systems, and socio-economic conditions. This localized approach will enhance the effectiveness and adoption of regenerative practices, ensuring that they are both practical and contextually relevant.

The integration of soil carbon sequestration into global climate initiatives and sustainability frameworks is expected to expand. International efforts aimed at achieving carbon neutrality and sustainable development goals increasingly emphasize the role of agriculture and land use. Initiatives promoting carbon farming and sustainable land management are gaining momentum, providing opportunities for scaling regenerative agriculture through coordinated global action. In addition, there is growing interest in nature-based solutions (NbS), where soil carbon sequestration is recognized as a key strategy for addressing environmental challenges^[31]. By aligning agricultural practices with natural ecosystem processes, regenerative agriculture contributes to biodiversity conservation, water management, and ecosystem restoration. This multifunctional approach is likely to attract increased investment from both public and private sectors.

The role of farmers as key stakeholders and innovators will be central to future progress. Participatory approaches that involve farmers in research, decision-making, and

knowledge exchange can accelerate the adoption of regenerative practices. Digital platforms and extension networks will further enhance access to information, enabling farmers to implement and adapt sustainable practices effectively. However, future progress will depend on addressing existing challenges, including economic barriers, policy gaps, and issues related to land tenure and equity. Ensuring inclusive participation, particularly of smallholder farmers, will be critical for achieving widespread impact. Financial instruments such as green funding, climate finance, and insurance mechanisms can support the transition toward regenerative systems, the future of soil carbon sequestration and regenerative agriculture is promising but contingent upon coordinated efforts across scientific, policy, and societal domains. Continued innovation, investment, and collaboration will be essential to unlock their full potential as solutions for climate-resilient and sustainable agriculture.

10. Conclusion

Soil carbon sequestration, integrated within the framework of regenerative agriculture, represents a scientifically grounded and practically viable pathway toward achieving climate-resilient farming systems. As agricultural landscapes face increasing pressure from climate change, land degradation, and resource scarcity, the need for sustainable and adaptive approaches has become more urgent than ever. This article has highlighted the critical role of soil organic carbon (SOC) in maintaining soil health, enhancing agricultural productivity, and mitigating climate change. Through regenerative practices such as reduced tillage, cover cropping, crop diversification, agroforestry, and the application of organic amendments, it is possible to increase carbon inputs to the soil, reduce carbon losses, and enhance long-term carbon stabilization. These processes collectively contribute to improved soil structure, water retention, nutrient availability, and biological activity. Beyond environmental benefits, soil carbon sequestration provides significant agronomic and socio-economic advantages. It supports stable crop yields, reduces dependence on external inputs, and enhances the resilience of farming systems to climatic stresses such as droughts and floods. These attributes are particularly important for smallholder farmers and vulnerable communities, where agricultural sustainability is closely linked to food security and livelihoods. However, the widespread adoption of soil carbon sequestration and regenerative agriculture requires overcoming several challenges, including measurement complexities, economic constraints, knowledge gaps, and policy limitations. Addressing these barriers necessitates a comprehensive approach that combines scientific research, technological innovation, financial incentives, and institutional support, the integration of soil carbon strategies into climate policies, the development of robust carbon markets, and the strengthening of extension services will be essential for scaling these practices. Collaboration among governments, research institutions, private sector actors, and farming communities will play a pivotal role in driving this transition, soil carbon sequestration through regenerative agriculture offers a holistic solution that aligns agricultural productivity with environmental sustainability. By restoring soil health and enhancing ecosystem resilience, it provides a pathway toward sustainable food systems capable of meeting the challenges of a changing climate. Continued

commitment to research, policy development, and farmer engagement will be crucial to realizing its full potential on a global scale.

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