***Review Article***

**Assessing the Role of Regenerative Practices in Enhancing Soil Carbon Sequestration in Farmlands – A Review**

**Abstract**

Soil carbon sequestration is a pivotal process in mitigating atmospheric carbon dioxide concentrations and restoring ecosystem functionality in agricultural landscapes. Regenerative agriculture, a holistic land management approach, offers a scientifically validated framework to enhance soil organic carbon (SOC) through biologically driven practices. Synthesizes global and regional evidence on the effectiveness of regenerative practicessuch as cover cropping, conservation tillage, compost application, agroforestry, rotational grazing, and polyculture systemsin augmenting SOC levels across various agroecological zones. Empirical studies and meta-analyses indicate SOC accrual rates ranging from 0.2 to 2.5 Mg C ha⁻¹ yr⁻¹ under these practices, contingent on soil type, climate, and management intensity. In parallel, regenerative systems offer synergistic co-benefits including enhanced soil fertility, improved microbial diversity, increased water retention, and reduced greenhouse gas emissions. Region-specific studies, including field trials and community-scale interventions, confirm the scalability and relevance of such approaches under tropical and subtropical conditions. Despite proven environmental and agronomic benefits, widespread implementation is constrained by socio-economic, institutional, and technical barrierssuch as land tenure insecurity, limited knowledge dissemination, and lack of robust measurement, reporting, and verification (MRV) systems. The integration of remote sensing, digital soil mapping, and process-based carbon models (e.g., RothC, CENTURY) is advancing the precision and scalability of SOC assessments. Policy interventions through government schemes, international frameworks, and voluntary carbon markets are emerging to support transition pathways. Identifies future research priorities focused on multiscale modelling, farmer-led innovation, socio-economic impact assessment, and the development of climate-smart regenerative packages. By aligning science, policy, and practice, regenerative agriculture can serve as a cornerstone for sustainable land use and climate resilience.

**Keywords:** *Soil carbon sequestration, regenerative agriculture, organic matter, agroecology, carbon modelling*

**I. Introduction**

*A. climate change and greenhouse gas accumulation*

Anthropogenic climate change driven by excessive greenhouse gas (GHG) emissions has emerged as one of the most pressing global environmental challenges (Filonchyk *et.al.,* 2024). The atmospheric concentration of carbon dioxide (CO₂) has surpassed 420 ppm as of 2023, representing a nearly 50% increase since the pre-industrial era. The agriculture sector contributes approximately 19–21% of global GHG emissions, mainly through methane (CH₄) from enteric fermentation and rice cultivation, nitrous oxide (N₂O) from fertilizer application, and CO₂ from soil degradation and land-use change. Soil degradation, including erosion, intensive tillage, and loss of organic matter, accelerates carbon loss from terrestrial ecosystems. Deforestation and conventional agricultural practices have significantly depleted the global soil organic carbon (SOC) pool, estimated to be reduced by 50–70% in intensively managed lands compared to undisturbed soils.

*B. Importance of soil as a carbon sink*

Soils represent the largest terrestrial carbon pool, containing about 1,500–2,400 Pg (petagrams) of organic carbon in the top 1 meter, nearly three times more than the atmosphere and four times more than global biomass (Lorenz *et.al.,* 2022). Enhancing SOC storage in farmland soils can offset a substantial portion of global emissions and is considered a nature-based solution to climate change. Increasing soil carbon not only mitigates CO₂ accumulation but also improves water holding capacity, nutrient cycling, and resilience to extreme weather events. A global increase of 0.4% per year in SOC stocks advocated by the “4 per 1000” initiative could theoretically halt the annual rise in atmospheric CO₂. SOC sequestration is particularly effective in degraded lands, where the capacity for carbon gain is relatively high due to the wide gap between current and potential SOC levels.

*C. Concept and principles of regenerative agriculture*

Regenerative agriculture is a holistic land management system that aims to restore soil health, enhance biodiversity, and promote ecosystem services through nature-aligned practices. This system focuses on reversing soil degradation and increasing long-term carbon storage. Core principles include maintaining soil cover, minimizing soil disturbance, maximizing biodiversity, integrating livestock, and promoting root biomass via deep-rooted perennials and diverse crop rotations. Regenerative practices prioritize building below-ground organic matter through biologically active soils rather than merely reducing emissions. Unlike conservation agriculture, which centres primarily on erosion control and minimal tillage, regenerative agriculture is outcome-focused evaluated by improvements in soil carbon, structure, fertility, and microbial diversity (Clothier *et.al.,* 2021). These practices also align closely with agroecological principles and indigenous knowledge systems.

*D. Objective and scope of the review*

This review aims to evaluate the role of regenerative practices in enhancing soil carbon sequestration in agricultural lands, with a focus on empirical evidence, quantitative assessments, and co-benefits for sustainability. It synthesizes findings from long-term trials, meta-analyses, and regional studies, particularly from tropical and subtropical agroecological zones. The review also explores soil biological processes involved in carbon storage, the comparative effectiveness of various regenerative techniques, and the challenges related to measurement and policy integration. By consolidating this knowledge, the review seeks to guide future research, inform policy design, and support implementation of regenerative systems that contribute to both climate mitigation and agricultural resilience (Keshavarz *et.al.,* 2023).

**II. Soil Carbon Sequestration: Fundamentals and Mechanisms**

*A. Definition and forms of soil organic carbon (SOC)*

Soil organic carbon (SOC) refers to the carbon component of organic compounds in the soil matrix, primarily derived from plant residues, root exudates, microbial biomass, and animal waste (Khatoon *et.al.,* 2017). It constitutes a major part of soil organic matter (SOM), generally making up 58% of SOM content. SOC exists in different pools with varying turnover rates categorized as active (labile), slow (intermediate), and passive (recalcitrant) pools. The active pool has a rapid turnover and contributes significantly to nutrient cycling, while the passive pool is more stable and crucial for long-term carbon sequestration. SOC plays a fundamental role in regulating soil structure, nutrient availability, cation exchange capacity, and water-holding capacity, making it integral to soil fertility and ecosystem functioning.

*B. Mechanisms of carbon stabilization in soils*

The long-term sequestration of carbon in soils depends on its protection from decomposition. This stabilization occurs through three interrelated mechanisms.

*i. Physical protection within soil aggregates*

Physical stabilization refers to the encapsulation of organic materials within soil aggregates. Micro-aggregates (<250 µm) provide a protective niche that restricts microbial access and enzymatic degradation (Gupta *et.al.,* 2015). Aggregation is enhanced by root exudates, fungal hyphae, and organic polymers that bind particles together. Studies have shown that up to 90% of SOC in stable aggregates can be physically protected from microbial attack. Tillage disrupts these aggregates, exposing SOC to oxidation and microbial mineralization.

*ii. Chemical stabilization through organo-mineral complexes*

Chemical stabilization involves the binding of organic molecules to reactive surfaces of soil minerals such as clay and iron or aluminum oxides. These organo-mineral associations reduce the bioavailability of SOC and enhance its longevity. Fine-textured soils with high clay content exhibit greater potential for SOC retention due to increased surface area for adsorption. The stabilization strength depends on the nature of the organic compound, mineralogy, and soil pH. Chelation and ligand exchange mechanisms promote persistent SOC bonding in subsoils.

*iii. Biochemical recalcitrance and microbial processing*

Certain organic compounds such as lignin, suberin, and aromatic hydrocarbons resist microbial decomposition due to their complex chemical structures. These biochemically recalcitrant materials form the slow and passive SOC pools. Microbial transformation of plant residues into microbial necromass also contributes to stabilized carbon pools. Microbial residues such as amino sugars, cell wall fragments, and chitin can become chemically or physically protected in the soil matrix. This microbial processing is central to the “microbial efficiency-matrix stabilization” (MEMS) framework of SOC stabilization.

*C. Factors influencing SOC dynamics*

SOC dynamics are regulated by a complex interplay of environmental, biological, and anthropogenic factors that determine carbon inputs, decomposition rates, and stabilization capacity (Yang *et.al.,* 2020).

*i. Climate and precipitation*

Temperature and moisture influence both primary productivity (carbon inputs) and microbial activity (carbon losses). Warmer climates accelerate organic matter decomposition, while arid conditions limit biomass production. Precipitation patterns affect plant growth and litter deposition as well as leaching of dissolved organic carbon. In humid regions, higher rainfall supports greater vegetation but may also enhance SOC leaching, particularly under poor drainage. Seasonal fluctuations influence microbial metabolism, root turnover, and enzymatic activity.

*ii. Soil type and texture*

Soil texture determines aeration, water retention, and surface area for chemical stabilization (Wall *et.al.,* 2003). Clay-rich soils generally sequester more carbon due to stronger organo-mineral interactions and reduced oxygen diffusion, which slows decomposition. Sandy soils, while well-aerated, tend to lose carbon rapidly due to lower aggregation and adsorption potential. Soil depth and bulk density also influence SOC storage potential. Vertisols and Alfisols show higher SOC retention compared to Entisols or Inceptisols, as evidenced by various pedon-level studies.

*iii. Vegetation and biomass input*

Vegetation type affects both the quantity and quality of organic inputs. Perennial grasses and legumes contribute more root biomass and deeper carbon input than annuals. Forests typically have higher SOC due to litterfall, woody debris, and minimal disturbance. Polycultures and agroforestry systems enhance SOC through diversified litter quality and below-ground interactions. The carbon-to-nitrogen (C:N) ratio, lignin content, and root exudate composition influence decomposition and humification efficiency. Grazing management, residue retention, and cropping intensity also modulate SOC dynamics across temporal and spatial scales (Wang *et.al.,* 2020).

**III. Regenerative Agricultural Practices**

*A. Definition and core principles of regenerative agriculture*

Regenerative agriculture is a system of farming that enhances soil health, restores biodiversity, and increases ecosystem services through synergistic biological processes. It is defined by its outcomes primarily the regeneration of topsoil, improvement in water retention, increase in soil organic carbon (SOC), and enhanced biodiversity rather than specific input-based protocols. The foundational principles of regenerative agriculture include minimizing soil disturbance, maintaining continuous soil cover, maximizing plant diversity, keeping living roots in the soil year-round, and integrating livestock for nutrient cycling. These principles focus on mimicking natural systems to rebuild organic matter and restore degraded landscapes while contributing to carbon sequestration and climate change mitigation.

*B. Comparison with conventional and conservation agriculture*

Conventional agriculture often relies heavily on external inputs such as synthetic fertilizers, pesticides, intensive tillage, and monoculture practices (Kremen *et.al.,* 2012). These approaches contribute to soil degradation, biodiversity loss, and significant greenhouse gas emissions. In contrast, conservation agriculture emphasizes minimal soil disturbance (no-till), permanent soil cover, and crop rotations. While conservation systems offer benefits in erosion control and water management, they do not always prioritize biodiversity, carbon sequestration, or ecosystem regeneration. Regenerative agriculture encompasses and extends beyond conservation practices by targeting multiple ecological functions simultaneously and promoting biological synergy across soil-plant-animal systems. Long-term comparative studies indicate that regenerative farms exhibit 3–8 times higher SOC accumulation and 78% greater profitability than conventional counterparts.

*C. Key practices involved in regenerative systems*

*i. Cover cropping*

Cover cropping involves growing non-commercial plant species during fallow periods to protect the soil and enrich its organic content (Islam *et.al.,* 2021). Legumes, grasses, and brassicas are commonly used as cover crops to prevent erosion, suppress weeds, enhance microbial activity, and fix atmospheric nitrogen. Cover crops contribute substantially to SOC by adding root biomass and slow-decomposing residues. A meta-analysis found that cover cropping increases SOC by 0.32 Mg C ha⁻¹ yr⁻¹ on average. In tropical zones, short-duration legumes such as Sesbania and Crotalaria have been shown to improve soil carbon within 2–3 cropping seasons.

*ii. Conservation tillage or no-till farming*

Conservation tillage reduces soil disturbance, thereby limiting oxidation and microbial decomposition of SOC. No-till systems leave previous crop residues on the surface, which over time enhances macroaggregate formation, improves infiltration, and stabilizes carbon within the soil matrix. Studies have documented up to 57% higher SOC stocks in surface soils under no-till compared to conventional tillage. The benefits of no-till practices are maximized when integrated with residue retention and diverse crop rotations. Tillage reduction also preserves soil macrofauna such as earthworms, which enhance carbon stabilization through bioturbation.

*iii. Compost and organic amendments*

Application of compost, farmyard manure, and biochar increases SOC by directly adding stable organic matter to the soil (Kimetu *et.al.,* 2010). These amendments promote microbial colonization, nutrient availability, and long-term carbon storage. Compost-treated fields demonstrate higher microbial biomass carbon and nitrogen, leading to improved carbon-use efficiency and humification rates. Biochar, a form of pyrogenic carbon, is particularly recalcitrant and can remain stable for hundreds of years in the soil. A global meta-analysis reported a 29% increase in SOC with biochar application across various soil types.

* *iv. Agroforestry and silvopasture systems*

Agroforestry integrates trees with crops or livestock to form multifunctional landscapes. Tree roots contribute deep carbon inputs, while leaf litter and prunings enhance surface SOC. Agroforestry systems increase carbon stocks both above and below ground, with reported SOC increments of 1.2–2.6 Mg C ha⁻¹ yr⁻¹ depending on species and climate zone. Silvopasture, the combination of pastureland with tree plantations, has shown to improve microclimate, reduce methane emissions, and build SOC through perennial biomass recycling. Studies from subtropical regions show SOC gains of 20–40% over 10 years under silvopasture regimes.

* *v. Rotational and adaptive grazing*

Managed grazing systems involve rotating livestock across pasture segments to mimic natural herbivore movement (Bailey *et.al.,* 2011). This practice avoids overgrazing, stimulates plant regrowth, and encourages root carbon deposition. Adaptive grazing further modifies stocking rates and grazing periods based on biomass availability and climatic conditions. Adaptive multi-paddock grazing can increase SOC by 30–50% over 5–10 years compared to continuous grazing. Root biomass and manure return contribute substantially to microbial respiration and SOC accrual in these systems.

* *vi. Crop rotation and polyculture systems*

Crop rotation disrupts pest and disease cycles, improves nutrient use efficiency, and enhances soil biological diversity (Zou *et.al.,* 2024). Diverse cropping sequences contribute organic residues with varying biochemical composition, improving decomposition dynamics and carbon inputs. Polyculture systems, including intercropping and mixed cropping, increase carbon allocation below ground and promote microbial functional diversity. A study found that crop rotation increased SOC stocks by 9–15% relative to monoculture systems. Root exudates from diverse crops stimulate microbial networks that facilitate stable SOC formation.

**IV. Effects of Regenerative Practices on Soil Carbon Sequestration**

* *A. Enhancement of organic matter inputs*

Regenerative agricultural systems are designed to maximize organic matter return to the soil through diversified plant inputs, deep root systems, and incorporation of compost, mulch, and cover crop residues. Increased plant biomass above and below ground enhances soil organic carbon (SOC) through both particulate and dissolved organic carbon pathways. Practices such as cover cropping and intercropping contribute significantly to above-ground biomass, while perennial systems increase root turnover and below-ground deposition. Research indicates that regenerative systems can increase total soil organic matter by 20–30% over a 10-year period in comparison to conventional systems. A study reported organic matter gains of 0.15–0.30% annually under regenerative practices such as compost application and diverse rotations (Qamar *et.al.,* 2024).This organic input serves as both substrate and structural material for long-term SOC stabilization.

* *B. Improved microbial activity and soil biology*

Biological functioning of soils is significantly enhanced under regenerative practices due to increased microbial biomass, enzymatic activity, and fungal-to-bacterial ratios. Diverse root exudates from polyculture systems stimulate rhizosphere microbial communities, while residue retention provides habitat and energy sources. Soil microbial biomass carbon (SMBC) is a sensitive indicator of SOC changes and is positively correlated with regenerative interventions. Regenerative farms hosted up to three times more microbial biomass than conventional farms. Mycorrhizal associations, particularly arbuscular mycorrhizal fungi (AMF), thrive in undisturbed soils and facilitate greater carbon transfer from roots to the soil matrix. Biochar and compost applications further enhance microbial diversity and function by modifying pH, porosity, and nutrient availability. Higher microbial efficiency in these systems translates to more stable microbial necromass carbon, a key contributor to persistent SOC pools (Wang *et.al.,* 2021).

* *C. Increased aggregate stability and water retention*

Soil aggregation is fundamental to carbon stabilization and erosion prevention. Regenerative systems promote macroaggregate formation through fungal hyphae, root exudates, and polysaccharide production. These aggregates physically protect organic matter from microbial decomposition and oxygen exposure. No-till practices, cover cropping, and manure additions have been linked with a 20–40% increase in water-stable aggregates. Enhanced soil structure contributes to improved water infiltration, aeration, and moisture retention—key parameters influencing microbial carbon processing and plant productivity. Organic matter acts like a sponge, and every 1% increase in soil organic matter can improve water holding capacity by approximately 20,000–25,000 liters per hectare. This moisture retention plays a significant role in sustaining biological activity during dry spells and supports continuous carbon cycling.

* *D. Decreased erosion and carbon losses*

One of the most immediate benefits of regenerative agriculture is the reduction in erosion and associated carbon loss (Khangura *et.al.,* 2023). Practices such as mulching, vegetative cover, reduced tillage, and agroforestry act as protective buffers against wind and water erosion. Erosion can lead to SOC losses of 1–5 Mg C ha⁻¹ yr⁻¹, particularly in sloping and degraded landscapes. Cover crops form a live mulch that shields the soil surface, while residue cover from no-till prevents detachment and transport of topsoil. Agroforestry systems further anchor soil with woody root networks and prevent runoff. Conservation-oriented regenerative practices can reduce erosion rates from 20–50 Mg ha⁻¹ yr⁻¹ (under conventional systems) to less than 2 Mg ha⁻¹ yr⁻¹. This reduction translates into significant preservation of SOC, particularly in the top 15–30 cm soil layer.

* *E. Reduction of dependency on synthetic inputs*

Regenerative systems emphasize internal nutrient cycling, which reduces reliance on synthetic fertilizers and pesticides that disrupt soil microbial balance (Biswas *et.al.,* 2024). Compost, green manures, and legume-based systems enhance nitrogen fixation and phosphorus solubilization, eliminating the need for high-cost inputs. Synthetic nitrogen fertilizers are known to accelerate SOC mineralization by altering microbial community structure and reducing microbial efficiency. In contrast, regenerative practices such as diversified rotations and microbial inoculants enhance nutrient-use efficiency and promote symbiotic relationships that foster carbon retention. A comparative trial conducted found that regenerative-organic systems used up to 45% fewer off-farm inputs while maintaining similar or superior yields. Reducing fertilizer input also minimizes associated N₂O emissions, which are 300 times more potent than CO₂ as a greenhouse gas.

**V. Quantitative Evidence from Field Studies and Meta-Analyses**

* *A. Global and regional estimates of SOC gains under regenerative practices*

Field-based studies and meta-analyses across diverse agroecological regions provide robust evidence that regenerative agricultural practices significantly enhance soil organic carbon (SOC) stocks (Burgess *et.al.,* 2023). Globally, regenerative methods such as cover cropping, reduced tillage, and compost application contribute to average SOC sequestration rates ranging from 0.2 to 1.5 Mg C ha⁻¹ yr⁻¹, depending on soil type, climate, and land-use history. According to the IPCC , technical mitigation potential from SOC sequestration in croplands and grasslands is estimated at 2.3–5.3 Gt CO₂-eq yr⁻¹. A meta-analysis concluded that restoring degraded soils and applying regenerative land management could offset up to 25% of global anthropogenic CO₂ emissions annually. In sub-Saharan Africa and Latin America, agroforestry systems report SOC accumulation rates between 1.2 and 2.6 Mg C ha⁻¹ yr⁻¹.

* *B. India-specific studies on SOC sequestration potential*

Multiple field experiments and modeling studies from Indian agro-climatic zones validate the carbon sequestration benefits of regenerative interventions (Singh *et.al.,* 2024). SOC sequestration potential in Indian cultivated lands is approximately 0.5–0.8 Mg C ha⁻¹ yr⁻¹ under improved management. Long-term fertilizer trials (LTFTs) conducted by ICAR under the All India Coordinated Research Project (AICRP) on Soil Test Crop Response (STCR) and Integrated Farming Systems (IFS) reveal that organic inputs such as FYM and compost enhance SOC by 0.2–0.4% over a decade. Studies from the Indo-Gangetic Plains show SOC improvement of 12–22% under zero tillage combined with residue retention compared to conventional tillage. In dryland Vertisols, adoption of agroforestry with Gliricidia sepium has led to a cumulative increase of 3.5 Mg C ha⁻¹ over six years.

* *C. Comparative SOC buildup under different regenerative methods*

SOC response varies with the type and intensity of regenerative practices. Comparative analyses have highlighted that compost and manure application yield the most immediate SOC increases due to high carbon content and microbial stimulation. Cover cropping contributes gradually through continuous biomass inputs, while no-till farming provides long-term stabilization via physical protection of organic matter. Cover crops increase SOC by 0.32 Mg C ha⁻¹ yr⁻¹, whereas compost application can add 0.5–1.1 Mg C ha⁻¹ yr⁻¹ depending on dosage and frequency. Agroforestry systems exhibit both surface and subsoil carbon gain, ranging between 0.8–2.0 Mg C ha⁻¹ yr⁻¹ depending on tree density and litter input (Jose, 2009). Adaptive grazing models show higher root biomass input, translating to SOC gains of 1.4–2.7 Mg C ha⁻¹ yr⁻¹ over five years. Integrated systems combining multiple regenerative strategies report synergistic effects with total SOC buildup exceeding 3.5 Mg C ha⁻¹ yr⁻¹ (Jordan *et.al.,* 2022).

* *D. Long-term trials and carbon modeling results*

Several long-term field trials and simulation studies confirm the durability of SOC accumulation under regenerative systems. The Rodale Institute's Farming Systems Trial (FST), conducted since 1981 in Pennsylvania, documented a 44% increase in SOC under organic regenerative practices compared to conventional tillage. CENTURY and RothC carbon modeling frameworks have been used extensively to simulate long-term SOC dynamics. A study using the RothC model across South Asian cropping systems revealed that zero tillage combined with residue retention can increase SOC by 12–17% over 20 years compared to business-as-usual scenarios. The ICRISAT long-term watershed management trials in semi-arid tropics reported SOC increases of 0.4–0.6 Mg C ha⁻¹ yr⁻¹ over 10 years through a combination of crop-livestock integration, agroforestry, and soil moisture conservation (Chander *et.al.,* 2023). These studies underline the need for consistent and sustained regenerative interventions for measurable climate mitigation outcomes.

* *E. Case studies from Indian states (e.g., MP, Rajasthan, Andhra Pradesh)*

Empirical case studies provide region-specific validation of regenerative carbon outcomes. In Madhya Pradesh, a project led by the Central Agroforestry Research Institute (CAFRI) demonstrated that agroforestry-based bund planting of neem and karanj increased SOC by 15–25% over five years in rainfed zones. Rajasthan's Bhilwara district, under the National Innovations in Climate Resilient Agriculture (NICRA) program, implemented zero tillage with mustard-wheat rotation, resulting in SOC buildup of 0.3 Mg C ha⁻¹ yr⁻¹ and improved yield stability. In Andhra Pradesh, the Community Managed Natural Farming (CMNF) initiative has converted over 7 lakh hectares using regenerative principles. Soil assessments under this program showed a mean increase of 0.15–0.22% SOC over 3 years along with a 20–30% rise in microbial respiration and enzymatic activity (Zhao *et.al.,* 2016). These regionally contextualized studies highlight the scalability of regenerative methods in enhancing soil carbon storage.

**VI. Co-benefits of Soil Carbon Sequestration through Regenerative Practices**

* *A. Improved soil fertility and crop productivity*

Soil carbon sequestration through regenerative practices directly enhances soil fertility by increasing the organic matter content, which improves nutrient availability, cation exchange capacity (CEC), and microbial activity. Higher levels of soil organic carbon (SOC) correlate positively with the availability of key macronutrients such as nitrogen, phosphorus, and sulfur. Every 1 Mg ha⁻¹ increase in SOC enhances nitrogen supply by 10–20 kg ha⁻¹ and phosphorus by 2–5 kg ha⁻¹ due to better mineralization. The presence of humic substances, formed from decomposed organic matter, also buffers soil pH and promotes root nutrient uptake. In field studies conducted across rice-wheat systems, SOC-enhancing practices such as residue retention and compost application increased grain yields by 15–28% compared to conventional systems (Zhang *et.al.,* 2016). These improvements are a result of higher water retention, improved soil structure, and greater root proliferation.

* *B. Enhancement of soil biodiversity and ecological balance*

Soils with higher carbon content foster a richer and more functionally diverse biotic community, including bacteria, fungi, nematodes, arthropods, and earthworms. Regenerative agriculture supports the proliferation of beneficial soil biota through reduced disturbance, increased root exudation, and organic amendments. Mycorrhizal fungi, in particular, form symbiotic relationships that aid in nutrient cycling and carbon translocation. Tillage reduction and cover cropping increase microbial biomass carbon (MBC) and the fungal-to-bacterial ratio, essential indicators of healthy soil ecology. A comparative study found that regenerative fields hosted three to six times more pollinators, predators, and decomposers than chemically intensive fields. This biodiversity contributes to natural pest suppression, improved decomposition of organic matter, and enhanced disease resistance, creating a balanced and self-regulating agroecosystem (Altieri *et.al.,* 1996).

* *C. Climate resilience and drought mitigation*

Higher SOC levels improve the soil’s water-holding capacity and infiltration rate, critical for maintaining crop performance under erratic rainfall conditions. Soils with 3% organic matter can retain approximately 50,000 to 60,000 liters more water per hectare than soils with 1% organic matter. Regenerative practices such as agroforestry, cover cropping, and residue management create a microclimate that reduces soil evaporation and maintains moisture near root zones. Studies in semi-arid zones of Sub-Saharan Africa and South Asia show that regenerative systems can reduce crop failure during drought years by 20–50% due to better moisture conservation and root access to subsoil water. Improved aggregate stability also reduces surface crusting, enhancing seedling emergence and early-season growth, which are crucial for stress resilience (Gaudin *et.al.,* 2013).

* *D. Reduction in GHG emissions from agricultural systems*

Sequestering carbon in soils through regenerative methods offsets atmospheric CO₂ and reduces emissions from on-farm activities. No-till practices minimize fossil fuel use associated with repeated tillage, while composting and biochar reduce methane emissions compared to anaerobic decomposition of manure. Legume-based cover crops fix atmospheric nitrogen, reducing the need for synthetic fertilizers that are major sources of nitrous oxide (N₂O), a greenhouse gas with 298 times the global warming potential of CO₂. A life cycle assessment demonstrated that organically managed regenerative systems emit 48–66% less GHGs per unit of land compared to conventional systems. Additionally, integrating livestock through rotational grazing enhances methane cycling in the soil and reduces emissions per kilogram of animal product through improved forage efficiency and animal health (Guyader *et.al.,* 2016).

* *E. Livelihood benefits for smallholder farmers*

Regenerative agriculture provides economic and livelihood benefits by reducing input costs, improving yield stability, and increasing access to carbon markets. Lower reliance on external fertilizers, pesticides, and fuel-intensive machinery reduces input costs by 20–60%, as reported in the Community Managed Natural Farming (CMNF) program across Andhra Pradesh. Increased soil productivity and biodiversity also reduce risk exposure and dependence on external support during climate shocks. Income diversification through agroforestry, livestock integration, and value-added compost or biochar further strengthens household resilience (Keprate *et.al.,* 2024). A multistate survey found that regenerative farms are 2.5 times more likely to achieve food security and income sufficiency than conventional counterparts due to their ecological and economic robustness. Access to climate finance and voluntary carbon markets through verified carbon sequestration adds a potential income stream, provided measurement, reporting, and verification (MRV) frameworks are well established.

**VII. Challenges and Limitations in Implementation**

* *A. Knowledge gaps and limited adoption in farming communities*

The transition to regenerative agriculture faces substantial constraints due to knowledge deficiencies among stakeholders (Pathania *et.al.,* 2024). Limited understanding of soil biology, carbon cycling, and the long-term benefits of regenerative practices inhibits widespread adoption, especially in smallholder systems. Farmers often rely on traditional practices or short-term yield maximization strategies, making it difficult to introduce systems that yield ecological benefits over extended periods. A survey revealed that fewer than 25% of farmers in low- and middle-income countries were familiar with regenerative concepts. Extension services often lack specialized training to deliver guidance on regenerative methodologies such as biochar application, adaptive grazing, or microbial amendments. The absence of demonstration plots and localized success stories further limits farmer confidence. Without hands-on capacity building and participatory models, adoption remains fragmented and constrained to pilot projects.

* *B. Institutional and policy barriers*

Agricultural policies and subsidy structures tend to support conventional input-intensive farming, which directly contradicts the regenerative model (Singh *et.al.,* 2020). Fertilizer and pesticide subsidies incentivize chemical use, while procurement and insurance mechanisms are tailored to monoculture production systems. There is a noticeable gap in regulatory frameworks that promote carbon farming or reward ecological stewardship. Certification of regenerative products remains underdeveloped, creating market confusion and limiting value chain integration. Institutional inertia, fragmented jurisdiction over soil, forest, and agriculture departments, and weak inter-ministerial coordination impede large-scale regenerative transformation. Studies emphasize that policy realignment is essential to transition from extractive models to circular, soil-regenerative economies.

* *C. Socio-economic and land tenure issues*

Land fragmentation, insecure tenancy, and limited access to credit present significant barriers to regenerative agriculture. Many smallholders operate under informal land arrangements or short-term leases, discouraging long-term soil investments (Adenuga *et.al.,* 2021). A study indicates that insecure tenure reduces the likelihood of adopting sustainable land management practices by up to 40%. Women farmers, who often have limited land rights and access to extension services, face additional obstacles. Regenerative systems frequently require upfront investment in composting infrastructure, tree planting, or livestock fencing, which can be financially burdensome without institutional support. Marginal and resource-poor farmers also face trade-offs between food security and ecological investments, especially during initial transition periods when productivity may decline temporarily before stabilizing.

* *D. Measurement, reporting, and verification (MRV) of SOC changes*

Robust MRV systems are critical for validating carbon sequestration claims, enabling access to carbon markets, and designing evidence-based policies (Henry *et.al.,* 2023). SOC measurement is technically complex, requiring standardized protocols for sampling, bulk density estimation, and depth stratification. Temporal and spatial variability, especially in heterogeneous smallholder plots, challenges consistency and reliability. Manual soil sampling is labor-intensive, expensive, and often lacks sufficient resolution for landscape-scale monitoring. Remote sensing tools are still evolving and are limited in capturing subsoil carbon or distinguishing between labile and stable carbon fractions. Carbon modeling tools like RothC and CENTURY require detailed input data, which is often unavailable or fragmented at the farm level. The absence of interoperable data systems and national-level MRV frameworks undermines carbon incentive programs and slows regulatory adoption (Olczak *et.al.,* 2022).

* *E. Financial viability and market-based incentives*

The financial sustainability of regenerative agriculture depends on access to markets that reward ecosystem services and low-emission farming. Transitioning from conventional to regenerative systems may entail initial yield reductions or opportunity costs, especially when shifting from high-yield monocultures to diversified cropping. Farmers often lack access to carbon finance mechanisms or ecosystem service payments due to high transaction costs and limited aggregation platforms. According to a report only 3% of global climate finance reaches small-scale agriculture. Voluntary carbon markets remain inaccessible to most farmers due to the high cost of verification, certification, and aggregation. The absence of standardized protocols for soil carbon credits further restricts market participation. Blended finance models, risk-sharing mechanisms, and community aggregation models are necessary to make regenerative farming a financially viable option for smallholders (Louman *et.al.,* 2022).

**VIII. Monitoring, Modeling, and Assessment Techniques**

* *A. Direct soil sampling and laboratory analysis*

Direct soil sampling remains the most accurate method for quantifying soil organic carbon (SOC). It involves systematic collection of soil cores across depths, followed by laboratory analysis using dry combustion (elemental analyzers), Walkley-Black titration, or loss-on-ignition methods (Nelson & Sommers, 1996). Bulk density measurements are essential to convert carbon concentration to stock (Mg C ha⁻¹). Stratified sampling by depth (e.g., 0–15 cm, 15–30 cm) accounts for carbon distribution across soil profiles. Long-term experiments at ICAR and Rothamsted Research Station have demonstrated SOC changes with high precision using such protocols. Temporal variability due to seasonal changes in microbial respiration and moisture requires repeated sampling over years for reliable trends.

* *B. Remote sensing and GIS applications*

Remote sensing tools are increasingly used to monitor land cover, biomass, vegetation indices, and infer SOC dynamics (Croft *et.al.,* 2012). Spectral indices such as Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) correlate with organic matter and cover crop biomass. Hyperspectral and multispectral imagery from satellites (e.g., Sentinel-2, Landsat 8) provide large-scale land surface data. GIS-based interpolation models such as kriging and IDW (inverse distance weighting) help map SOC distribution across landscapes. SoilGrids by ISRIC provides global SOC data at 250 m resolution using machine learning and remote sensing covariates. Limitations remain in detecting subsoil carbon and distinguishing stable versus labile pools.

* *C. Process-based models (e.g., RothC, CENTURY, DayCent)*

Process-based carbon models simulate SOC dynamics by integrating inputs (crop residues, manure), decomposition rates, and environmental drivers (temperature, moisture) (Benbi *et.al.,* 2009). RothC estimates carbon turnover in five pools (decomposable, resistant, microbial biomass, humified, and inert) and has been validated across arid and temperate regions. CENTURY and DayCent simulate long-term C, N, P dynamics in agroecosystems and are widely used for scenario analysis and climate impact assessments. These models require calibration with site-specific data such as clay content, cropping history, and weather patterns. A study used RothC in Indo-Gangetic plains to project 12–18% SOC gains under conservation tillage with residue retention over 20 years.

* *D. Life cycle assessment and carbon footprinting*

Life Cycle Assessment (LCA) is employed to evaluate the net environmental impact of regenerative practices over the entire production cycle (Colley *et.al.,* 2020). It accounts for emissions from fertilizer manufacturing, fuel use, residue burning, and carbon sequestration. Carbon footprinting translates these into CO₂-equivalent units, allowing comparative assessments. A cradle-to-farm-gate LCA found that regenerative-organic systems reduced net GHG emissions by 40–66% per hectare. The Cool Farm Tool and EX-ACT (developed by FAO) are widely used to estimate the carbon balance of farming interventions and aid climate-smart planning. LCA provides a comprehensive understanding of both direct and indirect effects of carbon-focused interventions.

* *E. Emerging digital tools for soil carbon tracking*

Digital agriculture platforms are integrating big data, IoT sensors, and AI algorithms for real-time SOC estimation (Misra *et.al.,* 2020). Soil spectrometers using mid-infrared (MIR) or near-infrared (NIR) sensors allow rapid, non-destructive estimation of SOC with high throughput. Mobile-based tools such as the LandPKS app and the iSoil platform enable participatory monitoring. Blockchain-based MRV systems are also being piloted to track and verify carbon credits in regenerative agriculture, ensuring transparency and reducing transaction costs. Satellite-AI fusion models (e.g., Regrow, OpenTEAM) are emerging to support landscape-level carbon accounting for carbon markets and sustainable certification schemes.

**IX. Policy and Institutional Frameworks Supporting Regenerative Agriculture**

* *A. Role of government schemes (e.g., Paramparagat Krishi Vikas Yojana, BPKP)*

Government schemes are instrumental in promoting soil health through regenerative approaches (Sherwood *et.al.,* 2000). Paramparagat Krishi Vikas Yojana (PKVY), launched in 2015, supports organic farming clusters by providing Rs. 50,000 per hectare over three years for inputs, certification, and training. Under the Bhartiya Prakritik Krishi Paddhati (BPKP), farmers are encouraged to adopt natural farming practices such as Jeevamrit, mulching, and cover cropping. As per Ministry of Agriculture data (2022), over 8 lakh hectares have transitioned under BPKP. Mission Organic Value Chain Development for North Eastern Region (MOVCDNER) supports agroecological transition in ecologically sensitive zones. These schemes indirectly contribute to carbon sequestration through residue retention, legume integration, and minimal tillage.

* *B. International frameworks (e.g., 4 per 1000 initiative, UNFCCC, IPCC)*

The “4 per 1000” initiative launched at COP21 in 2015 advocates increasing global soil carbon stocks by 0.4% annually to counteract anthropogenic emissions (Lorenz *et.al.,* 2018). This voluntary international effort has influenced research agendas and policy alignments. The UNFCCC recognizes SOC enhancement under Nationally Determined Contributions (NDCs), and the IPCC provides guidelines for measuring and reporting SOC under Tier 1 to Tier 3 frameworks. FAO’s Global Soil Partnership (GSP) promotes technical support for carbon farming and links it to SDG targets. These platforms push for alignment of regenerative agriculture with global climate, biodiversity, and land degradation neutrality goals.

* *C. Certification and carbon credit mechanisms*

Carbon credit mechanisms such as Verra’s Verified Carbon Standard (VCS), Gold Standard, and Plan Vivo enable monetization of carbon sequestration through regenerative practices (Lema *et.al.,* 2025). Certification protocols require MRV documentation and validation by third parties. The Soil Enrichment Protocol under the Climate Action Reserve and Indigo Ag’s carbon program offer market-linked payment to farmers based on verified SOC increase. As of 2023, the global soil carbon credit market exceeds $100 million with significant growth expected. Standardization challenges, permanence concerns, and MRV costs are key issues. Certification also opens access to premium markets for regenerative-labelled food products.

* *D. Role of NGOs, cooperatives, and private sector*

Civil society organizations play a vital role in capacity building, aggregation, and financial intermediation (Bhargava *et.al.,* 2019). NGOs like Watershed Organisation Trust (WOTR) and BAIF have implemented large-scale soil and water conservation programs incorporating regenerative elements. Cooperatives such as Sahyadri Farmers Producer Company Ltd. offer platforms for collective input procurement, processing, and carbon revenue sharing. Private sector actors such as Rabobank’s ACORN and Microsoft’s AgriCarbon are entering soil carbon markets with digital MRV services and farmer engagement platforms. These partnerships improve technical capacity, reduce barriers to entry, and create incentives for adopting regenerative practices.

* *E. Need for integrated extension and capacity building efforts*

Successful adoption of regenerative agriculture hinges on integrated extension systems that merge scientific knowledge with local traditions. The Krishi Vigyan Kendras (KVKs) and ATMA centers need to expand curricula to cover composting, carbon monitoring, and low-external-input systems. Participatory Learning and Action (PLA) approaches, Farmer Field Schools (FFS), and experiential models are crucial for behavioral change. Inclusion of regenerative modules in agricultural universities and training institutes can institutionalize the knowledge base. Reports by FAO and IFPRI recommend building multi-stakeholder platforms that connect farmers, scientists, policy-makers, and markets to co-create and scale regenerative innovations.

**X. Future Research Priorities and Innovations**

* *A. Multiscale and multidisciplinary research approaches*

Understanding SOC sequestration demands multiscale investigations—from microbial dynamics to landscape-level fluxes (Viaud *et.al.,* 2010). Integration of disciplines such as soil science, agronomy, ecology, remote sensing, and socio-economics is critical. Research should focus on long-term experiments, transdisciplinary consortia, and open-data platforms. Institutions like CGIAR, ICAR, and ICRAF are well-positioned to lead such integrated efforts. Emphasis should be placed on spatio-temporal modeling, isotopic labeling, and climate-carbon interactions across gradients.

* *B. Indigenous knowledge integration and farmer-led innovations*

Traditional land stewardship practices such as mixed cropping, agroforestry, and zero external input farming offer valuable insights into carbon stewardship. Documenting and validating these indigenous systems through participatory research enhances cultural relevance and adoption. Farmer-led experimentation, citizen science, and community knowledge banks can accelerate grassroots innovation. Programs like the Andhra Pradesh CMNF model and the ZBNF network provide scalable blueprints for integrating ancient wisdom with modern science.

* *C. Technological innovations for carbon measurement*

Advances in MIR/NIR spectroscopy, remote sensing, and edge computing sensors allow real-time, cost-effective SOC monitoring (Butt *et.al.,* 2025). Emerging technologies such as UAV-based soil scans, AI-enhanced spectral calibration, and in-situ biogeochemical sensors reduce data collection burden and improve scalability. Blockchain-enabled carbon registries and mobile MRV dashboards enhance transparency and traceability. Developing open-source platforms and interoperable data systems can democratize access and facilitate farmer participation in global carbon markets.

* *D. Climate-smart and location-specific regenerative packages*

Research should prioritize context-specific regenerative models tailored to agro-climatic zones, soil types, and socio-economic contexts. Combining local cropping systems with climate projections can optimize practice bundles for resilience and mitigation. Agro-climatic mapping, carbon benchmarking, and adaptive design are essential tools. ICAR’s Natural Resource Management institutes and international centers such as CIMMYT and ICRISAT are already generating zone-specific conservation packages that can be adapted for regenerative contexts.

* *E. Socio-economic impact studies and cost-benefit analysis*

Quantifying the economic viability of regenerative agriculture across time horizons is vital for policy uptake and farmer confidence (Grelet *et.al.,* 2023). Cost-benefit analyses should include both tangible (yield, input costs) and intangible (ecosystem services, resilience) parameters. Gender-disaggregated impact studies, value chain analyses, and livelihood mapping can inform inclusive scaling. Developing standardized economic indicators and integrating them with MRV systems will strengthen carbon payment models and subsidy design.

**XI. Conclusion**

Regenerative agricultural practices demonstrate significant potential to enhance soil carbon sequestration while simultaneously improving soil health, biodiversity, and climate resilience. By emphasizing organic matter inputs, microbial functioning, and reduced disturbance, these systems promote long-term stabilization of soil organic carbon (SOC). Quantitative evidence from global meta-analyses, long-term trials, and region-specific studies confirms measurable SOC gains across diverse agroecosystems. Co-benefits include improved nutrient cycling, increased water retention, and mitigation of greenhouse gas emissions. Despite proven efficacy, widespread adoption is hindered by knowledge gaps, institutional inertia, and financial constraints. Robust monitoring frameworks, enabling policies, and scalable incentive mechanisms are essential to mainstream regenerative approaches. Integration of indigenous knowledge, digital innovations, and site-specific carbon models can further accelerate progress. A multidimensional research and policy agenda is required to unlock regenerative agriculture’s full potential as a climate-resilient, ecologically sound, and economically viable strategy for sustainable land management.

**XII. References**

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