SATSA Mukhapatra - Annual Technical Issue ***30*** *: 2026* ISSN 0971-975X ***Invited Paper***

Trade-Offs Between Soil Organic Carbon Storage and GHGs Emissions Under Regenerative Agriculture

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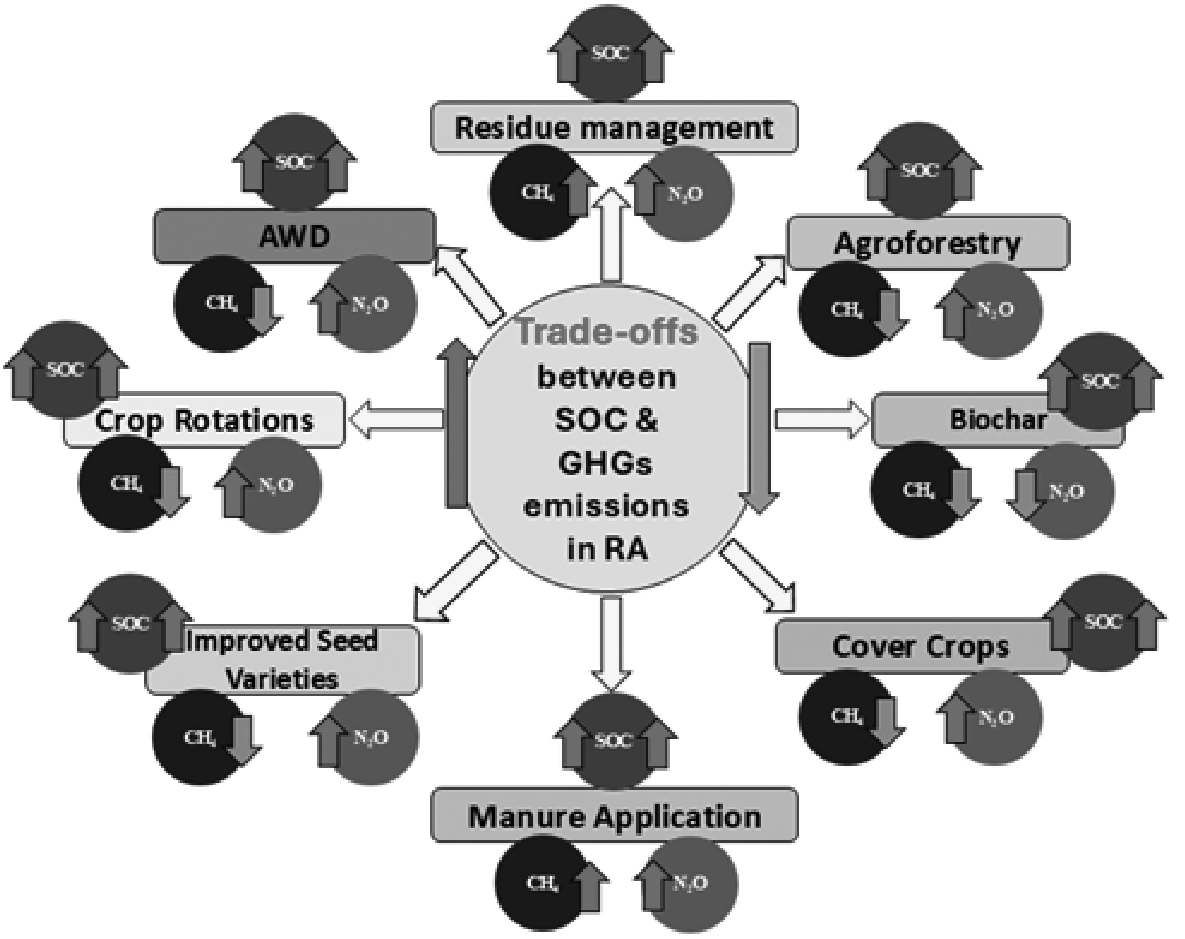
(Received : November 17, 2025; Revised : January 07, 2026; Accepted : January 08, 2026)

GRAPHICAL ABSTRACT



Introduction

In an era marked by escalating climate change, regenerative agriculture (RA) plays a vital role in reducing greenhouse gases (GHGs) emissions and enhancing soil carbon storage (Kabato *et al.*, 2025). The RA's techniques, such as no-till farming,

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cover cropping, and managed grazing increase organic matter in the soil, which acts as a carbon sink, and reduce the use of synthetic fertilizers and excessive tillage, however, which release potent GHGs like nitrous oxide (N_2O) and carbon dioxide (CO_2) (Basheer *et al.*, 2024). Soil organic matter acts as a vital food source for soil microbes, supporting key processes such as nutrient cycling and decomposition that are fundamental to soil health (Nair *et al.*, 2022; Khangura *et al.*, 2023). By increasing organic matter levels, RA improves soil structure, boosts water-holding capacity, and enhances nutrient availability, thereby influencing a more resilient and productive farming system (Liang *et al.*, 2025). Although the global potential of RA to mitigate climate change is widely recognized, the reality is more complex (La *et al.*, 2025). Trade-offs between soil carbon sequestration and GHGs emissions remain a critical concern, raising questions about the net climate benefits of RA in practice.

The trade-offs in RA lies between increasing soil carbon storage and the rise of higher methane (CH_4) emissions when organic amendments such as manure and compost are applied (Filonchyk *et al.*, 2024). While soil carbon sequestration is beneficial for climate change mitigation, its potential to emit relatively more GHGs than organic input-agriculture could cause positive climate change feedback (Lal *et al.*, 2020). The RA practices present a promising approach to address regional agricultural challenges while simultaneously offering opportunities for climate change adaptation and mitigation (Kyriakopoulos *et al.*, 2023). Techniques such as cover cropping, crop rotation, reduced tillage, agroforestry, and integrated animal grazing not only enhance soil organic carbon (SOC) but also contribute to restoring soil fertility (Fahad *et al.*, 2022). The SOC is of particular importance in regenerative systems, as soils function both as a source and sink of atmospheric carbon, and SOC serves as a key indicator of soil health and agricultural productivity (Sher *et al.*, 2024). The RA practices also contribute to biodiversity conservation, sustain water and nutrient dynamics, stabilize crop yields, and support climate resilience (Liang *et al.*, 2025). To maximize these benefits, supportive policies, such as incentives for ecosystem services, carbon credit schemes, and sustainable land management frameworks, are necessary for scaling up RA practices and ensuring long-term environmental and socio-economic benefits (Figure 1).

The RA is attracting the attention of policymakers, farmers, and investors due to its potential to address both climate change and food security challenges (Zougmoré *et al.*, 2021). Policymakers are exploring the role of agricultural lands in achieving their Nationally Determined Contributions (NDCs), not only by reducing GHGs emissions from agriculture but also by enhancing C-sequestration (Raj *et al.*, 2025). Furthermore, national and regional policies are expected to prioritize the large-scale adoption of regenerative practices. At the same time, private investors are recognizing opportunities for profit through agricultural carbon credit projects, which incentivize farmers to adopt regenerative practices that reduce emissions and increase SOC stocks (Cherubin *et al.*, 2024). The benefits of RA are quantified by comparing carbon sequestered against

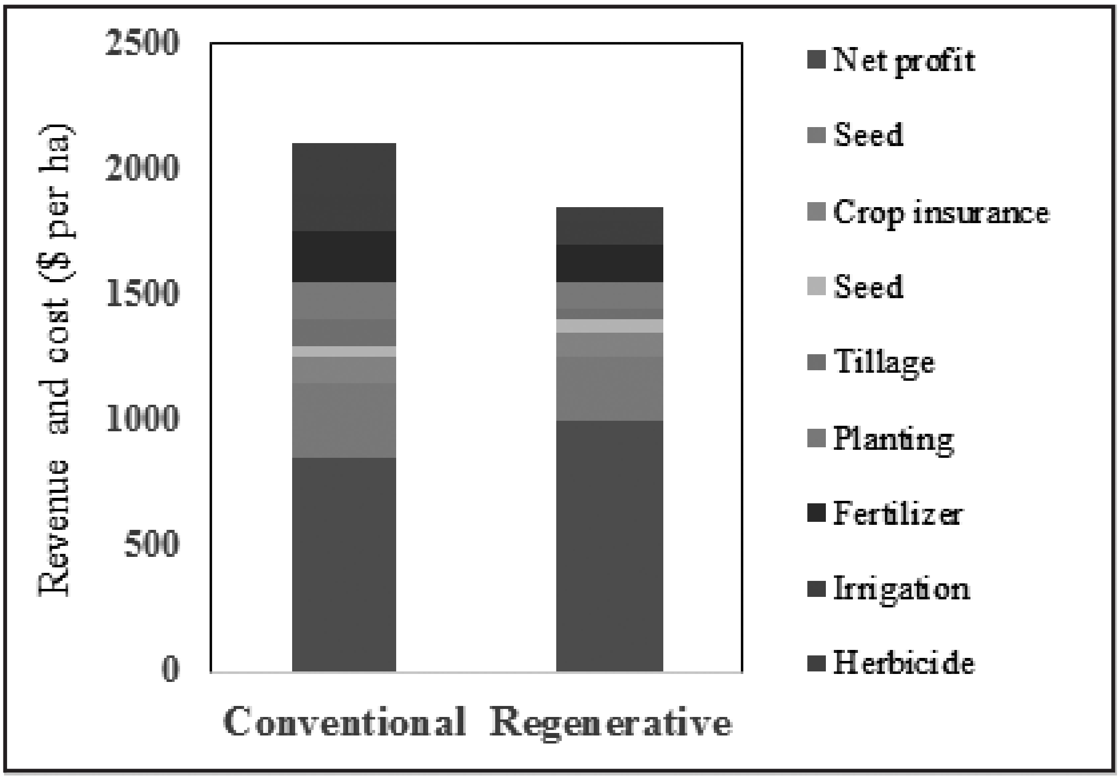

Figure 1. Regenerative systems generate nearly twice the profit of conventionally managed fields (LaCanne *et al.*, 2018)

a baseline scenario, generating tradable carbon credits. Together, supportive policies and investment mechanisms are likely to accelerate the scaling up of RA.

This article aims to review the trade-offs between GHGs emissions and soil carbon storage under various RA practices. While RA is often presented as a "win–win" approach, interactions among CO_2, CH_4, and N_2O highlight the possibility of promoting positive climate change feedback. Therefore, in this review, we emphasize regenerative agriculture (RA) as a set of practices that improve soil fertility through increased SOC, while highlighting the trade-offs between carbon sequestration and potential increases in GHGs emissions.

Bibliometric Assessment on Regenerative Agriculture, Soil Carbon, and GHGs Emissions

The bibliometric analysis was conducted to understand research trends linking regenerative agriculture, soil carbon sequestration, and greenhouse gases (GHGs) emissions. Using the Web of Science database (2010-2025), three separate searches were performed: (1) regenerative agriculture and soil carbon, (2) regenerative agriculture and GHGs emissions, and (3) trade-offs between soil carbon storage and GHGs emissions. The analysis revealed that most studies focus on carbon sequestration potential, nitrous oxide and methane fluxes, and climate-smart practices such as cover cropping, no-tillage, and residue management (Figure 2). Research hotspots are concentrated in the USA, China, India, and European countries, with strong clusters around "soil organic carbon," "greenhouse gases," and "sustainable agriculture." However, limited integration of economic co-benefits and system-level trade-offs highlights a major research gap. This review highlights on these findings to evaluate the dual role of regenerative agriculture in enhancing soil carbon storage while managing GHGs emissions.

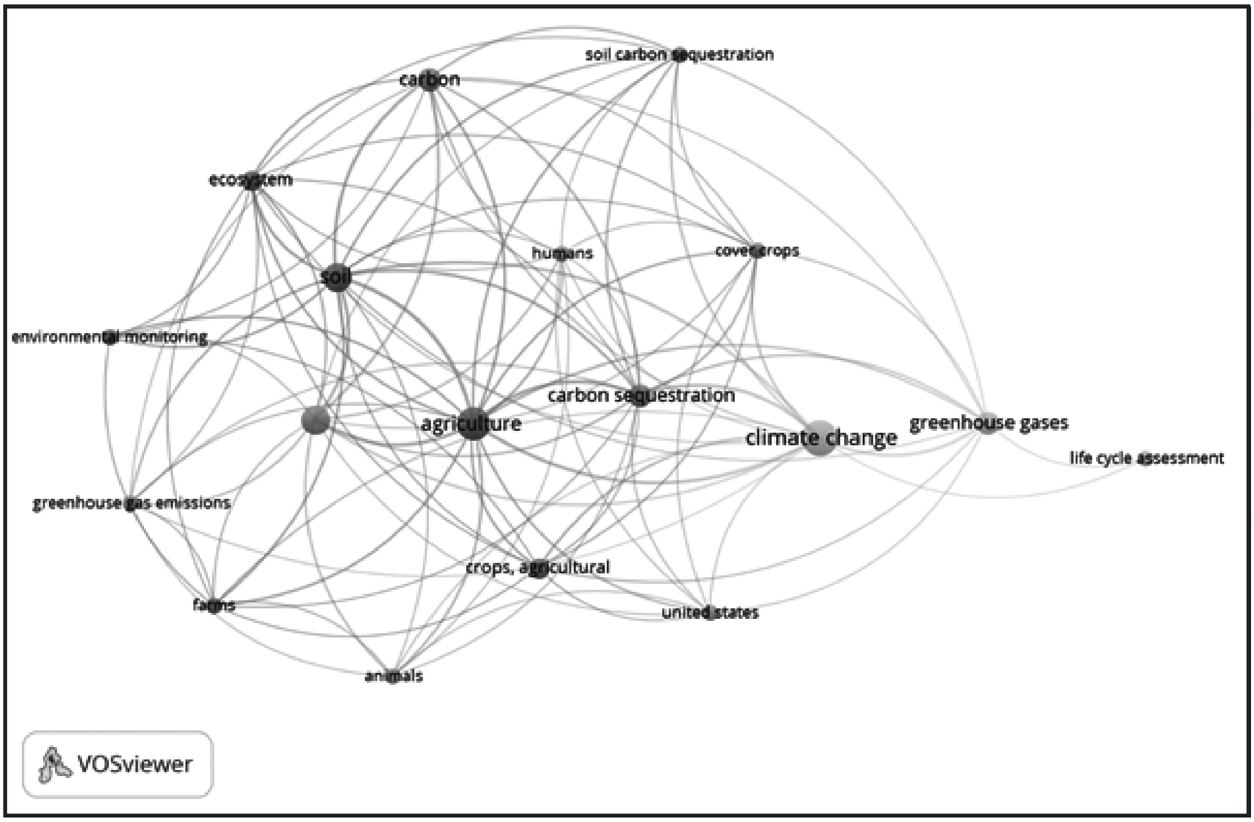

Figure 2. Keyword co-occurrence network related to regenerative agriculture, soil organic carbon, and greenhouse gas emissions research, generated using VOSviewer based on Web of Science database (2010-2025). Node size indicates frequency of occurrence, and link thickness shows co-occurrence strength.

Regenerative Agriculture : Concepts, Practices, and Relevance

Regenerative agriculture comprises a diverse set of practices that primarily target biological and ecological systems to enhance crop productivity and restore landscape function (Sher *et al.*, 2024). It includes maintaining continuous soil cover, minimizing soil disturbance, retaining living plant materials in the soil over the long time, enhancing soil biodiversity, integrating livestock with crops, and reducing reliance on synthetic fertilizers and herbicides (Singh *et al.*, 2024).

The adoption of these practices offers several benefits, including improved soil health through increased SOC, enhanced microbial diversity, and mitigation of GHGs emissions (Srivastava *et al.*, 2025). Prior to implementing RA, factors such as soil type, temperature, precipitation, and farmer preferences must be carefully considered (Khangura *et al.*, 2023). Many RA practices overlap with established "good farming" techniques, and some are already advocated within conventional systems (Drizo *et al.*, 2022). Additionally, RA incorporates elements from conservation agriculture, sustainable agriculture, climate-smart agriculture, and organic farming.

Mechanisms of GHGs Mitigation through Regenerative Agriculture

Several claims have been made regarding the role of RA in reducing GHGs emissions. Such as,

- Minimize bare soil and maintain living roots in the ground whenever possible
- Reduce soil disturbance, such as through limited tillage
- Promote and harness biodiversity, including plants, microbes, insects, birds, and livestock
- Limit the use of external synthetic inputs
- Manage livestock strategically, for example through adaptive multi-paddock grazing

Soil Carbon Dynamics under Regenerative Agriculture

The key principles of RA, such as maintaining soil cover, reducing tillage, enhancing plant diversity, and strategic livestock management, are generally beneficial for sustaining and increasing SOC stocks (Francaviglia *et al.*, 2023). Table 1 summarizes the sequestration potential and associated costs of major soil carbon enhancing techniques (IPCC, 2022; CEEZER data). Bare soils accelerate carbon loss through respiration and erosion, whereas practices like cover cropping, minimal tillage, and diversified plant systems contribute to higher SOC retention, though outcomes vary with soil type, climate, and management strategies (Hussain *et al.*, 2021). Stanley *et al.* (2025) suggested that grassland and grazing systems with adaptive multi-paddock (AMP) grazing can enhance soil organic matter compared to conventional grazing. However, long-term and optimized studies are still required to quantify the rate of SOC sequestration under RA and to evaluate potential trade-offs with other greenhouse gas emissions, ensuring a more precise assessment of its net climate change mitigation potential.

Plant Diversity and Methane Mitigation through Improved Forage Quality

Increased plant diversity in RA systems not only enhances soil health and ecosystem resilience but also improves the nutritional quality of forage for grazing animals (Teague *et al.*, 2020). Diverse pastures, with a mix of legumes, grasses, and deep-rooted species, generally provide higher protein content, better digestibility, and balanced nutrient availability compared to monoculture systems (Ohiwal *et al.*, 2025). This improved forage quality leads to greater feed efficiency and reduced enteric fermentation, thereby lowering CH_4 emissions from ruminants. Moreover, plant

Table 1. Soil carbon enhancing techniques (IPCC, 2022)

	Description	Sequestration potential (Gt CO_2/year)	Price per credit ($)
Regenerative agriculture (agroforestry)	Accumulation of soil organic carbon via a range of practices	Soil carbon sequestration in croplands and grasslands: 0.6-9.3Agroforestry: 0.3-9.4	$15-80
Biochar	Transformation of plant and wood residuals into plant-based coal that can be added to soil as natural fertilizer	0.3-6.6	$100-250
Enhanced weathering	Mineralization of atmospheric CO_2 on rocks as soil inorganic carbon	2.0-4.0	$250-500
Inorganic soil carbon	Acceleration of atmospheric CO_2 mineralization by microbes into bicarbonate and carbonate minerals	Not specifically quantified (variable)	$75-150

secondary compounds such as tannins and saponins, often present in diverse forage species, have been shown to directly inhibit methanogenesis in the rumen (Kolesnik *et al.*, 2024). However, mainly *Asparagopsis* (seaweed)-based feed to rumen has been demonstrated to remain effective and anti-methanogenic without negative impacts on rumen function and at low inclusion levels in animal diets (Roque *et al.*, 2019). Thus, fostering plant diversity offers a dual benefit, supporting biodiversity conservation and reducing agricultural CH_4 emissions through sustainable livestock nutrition.

Methanotrophic Potential of Regenerative Agriculture Soils

Soils managed under RA practices often exhibit enhanced methanotrophic activity, which contributes to the reduction of atmospheric CH_4 (Jiang *et al.*, 2022). Methanotrophs are specialized soil microorganisms that oxidize CH_4 as their primary energy source and play a crucial role in regulating CH_4 fluxes between soils and the atmosphere (Lim *et al.*, 2024). Practices in RA, such as reduced tillage, organic amendments, diversified cropping systems, and improved soil structure, create favorable conditions for methanotroph abundance and activity (Devi *et al.*, 2024). Improved aeration, higher organic matter, and stable soil aggregates support methanotrophic communities, enabling RA soils to act not only as carbon sinks but also as effective biological filters for CH_4 (Lim *et al.*, 2024). This microbial-driven process highlights the dual climate benefit of RA soils: enhancing soil organic carbon storage while simultaneously reducing CH_4 concentrations through natural oxidation pathways.

Reduced Nitrous Oxide Emissions from Regenerative Agriculture Soils

The RA's soils are often associated with lower N_2O emissions compared to conventionally managed soils (Hassan *et al.*, 2022). This reduction is primarily linked to improved soil structure, higher organic matter, and balanced nutrient cycling that minimize conditions favorable for nitrification-denitrification-driven N_2O release (Chinthalapudi *et al.*, 2025). Practices such as cover cropping, diversified rotations, organic amendments, and precision nutrient management enhance nitrogen-use efficiency while reducing reliance on synthetic fertilizers, which are major contributors to N_2O emissions (Zhang *et al.*, 2023). Additionally, the integration of deep-rooted and nitrogen-fixing species improves natural nitrogen uptake by crops, leaving less residual nitrogen available for conversion into N_2O. By stabilizing the soil environment and optimizing nutrient flows, soils under RA practices contribute to lowering one of the most potent agricultural greenhouse gases, thereby strengthening their role in climate change mitigation (Kabato *et al.*, 2025).

Trade-offs of C-sequestration and GHGs Mitigation in Regenerative Agriculture

While the RA provides significant potential for reducing GHGs emissions and enhancing soil carbon sequestration, certain trade-offs exist (Maenhout *et al.*, 2024). The use of manure, compost, or other organic amendments enriches soil organic matter but could also increase CH_4 emissions (Bumb *et al.*, 2021). Similarly, improved forage quality can reduce CH_4 emissions per unit of animal product, yet overall emissions may remain substantial with an increasing livestock population. The stability of sequestered soil carbon is another concern, as quick labile carbon gains can be reversed through erosion, drought, or shifts in management practices (Noordwijk *et al.*, 2015). In some cases, lower yields observed under RA could also prompt agricultural expansion, indirectly adding to global GHGs emissions. Addressing these trade-offs requires integrated, long-term strategies and region-specific evaluations to maximize RA's net climate benefits.

Key Practices of Regenerative Agriculture and their role of in Trade-offs

Agroforestry

Agroforestry includes trees and shrubs within croplands, enhancing SOC through higher litter input and root biomass, while offering multiple ecosystem services such as biodiversity support, microclimate regulation, and improved nutrient cycling (Fahad *et al.*, 2022). However, mineralization of nitrogen-rich litter could increase N_2O emissions, and shaded, moisture-rich soils may create anaerobic conditions favorable for CH_4 production, particularly in flooded rice systems (Kandula *et al.*, 2025). Evidence suggests that agroforestry systems, such as crop-shade tree combinations, generally accumulate higher SOC compared to monocultures (Fahad *et al.*, 2022). However, the extent of climate benefits is shaped by tree species, soil type, and management practices, with gains in carbon sequestration potentially offset by elevated GHGs emissions. This indicates that realizing the full potential of agroforestry as a climate-smart strategy requires careful balancing of SOC storage with GHGs emissions.

Biochar

Biochar is a carbon-rich product produced by pyrolysis of organic materials, and its application to soils can enhance SOC by protecting carbon from microbial decomposition through a negative priming effect and enhance the passive carbon pool in soil (Pandian *et al.*, 2024). While biochar generally increases SOC stocks over time, its impact on GHGs emissions are variable. Many studies report reductions in N_2O and CH_4 emissions, but CO_2 emissions can increase depending on soil type, biochar properties, and management practices. These outcomes highlight a trade-off between biochar in improving long-term carbon storage while potentially altering soil-CO_2 emissions.

Compost

Compost application enhances SOC by supplying organic matter and improving soil fertility, structure, and microbial activity. By contributing humified carbon, compost can build passive SOC pools compared to fresh residues or raw manure. However, its decomposition also introduces readily available labile carbon that can influence microbial respiration, increasing CO_2 emissions due to metabolism, and under anaerobic conditions may stimulate methanogenesis, leading to the release of CH_4. Several studies have reported elevated CH_4 and N_2O fluxes following compost addition, while others have observed minimal or even reduced emissions, highlighting the role of compost on soil type and management practices. However, the addition of compost tends to stabilize carbon more effectively and generate less GHGs than partially decomposed material. Moisture and aeration further influence the trade-offs: waterlogged and anoxic soils may create hotspots for CH_4, whereas well-drained soils favor SOC retention with lower fluxes. The trade-off, therefore, lies between the potential for compost to enhance SOC stocks and the possible CH_4/CO_2 emissions. However, integrating compost with complementary practices such as biochar, cover crops, or reduced tillage can help offset its emissions while retaining its carbon storage benefits.

Cover Crops

Cover crops, such as legumes, grasses, or mixed species, are grown during fallow periods or alongside main crops to improve soil cover, nutrient cycling, and biomass input to soils (Scavo *et al.*, 2022). They contribute to soil organic carbon (SOC) accumulation through the addition of aboveground residues and root biomass, as well as by stimulating microbial activity that stabilizes organic matter (Almagr *et al.*, 2021). Cover crops also reduce soil erosion and improve water infiltration, indirectly preserving SOC (Haruna *et al.*, 2020). However, the decomposition of nitrogen-rich residues, especially legumes, can increase N_2O emissions, a potent greenhouse gas, creating a trade-off between the benefits of SOC sequestration and GHGs emissions. The timing of cover crop removal, residue management, and species selection can strongly influence this balance, making the net climate impact context-dependent (He *et al.*, 2025). Despite these trade-offs, cover cropping is generally considered a climate-smart practice when managed to optimize residue incorporation and minimize N_2O losses.

Manure Application

Manure is widely used to enhance soil fertility and increase SOC by supplying organic carbon and nutrients that stimulate microbial activity (Bhatt *et al.*, 2019). The addition of manure can improve soil structure, water-holding capacity, and nutrient retention, all of which support long-term carbon storage (Wang *et al.*, 2025). At the same time, manure provides a substrate for microbial processes that generate CH_4, particularly under wet, compacted, or anaerobic soil conditions (Hou *et al.*, 2015). These emissions can partially offset the climate benefits of increased SOC, representing a trade-off between carbon storage and GHGs fluxes in manure use (Rumpel *et al.*, 2023). Optimizing manure type, application rates, timing, and combination with other practices like cover crops or reduced tillage can reduce these emissions while maintaining the SOC gains, highlighting the importance of integrated management for achieving net climate benefits (Vending *et al.*, 2023).

Improved Seed Varieties

The adoption of improved or high-yielding crop varieties can enhance SOC by increasing belowground biomass, root density, and residue return to soils. Robust root systems contribute to carbon input and more stable soil organic matter (Raj *et al.*, 2025). However, the cultivation of improved varieties often requires higher nutrient inputs, especially nitrogen fertilizers, which can elevate N_2O emissions if not managed carefully. The trade-off is therefore between the potential for increased carbon sequestration due to greater biomass inputs and the risk of elevated GHGs emissions associated with intensified nutrient management. Aligning improved crop genetics with optimized fertilization, cover cropping, and soil conservation strategies is critical to maximize SOC benefits while minimizing greenhouse gas release.

Crop Rotations

It is the planned sequencing of different crops in the same field, which is widely recognized for improving soil fertility, pest and weed control, and yield enhancement. From a carbon storage perspective, crop rotation can enhance SOC through diversified root systems, higher organic inputs, and improved soil aggregation, which together build passive carbon pools. The diversity and frequency of rotations significantly influence the outcomes, such as legumes may provide nitrogen inputs that boost SOC while simultaneously raising the N_2O emissions due to increased mineral nitrogen availability for microbial processes. Studies in Southeast Asia show that double and triple cropping systems often deliver SOC gains, but frequent tillage between rotations can release CO_2 by accelerating the decomposition of soil organic matter, by offsetting carbon gains (Tan and Kuebbing, 2023). Furthermore, triple rotations involving legumes increased carbon inputs but also led to SOC losses when soils were tilled intensively. The trade-off is therefore between the potential of crop rotations to build SOC through diversification and root biomass, and the rise in elevated GHGs fluxes, particularly N_2O from legume-rich rotations and CO_2 from repeated tillage activities.

Organic Farming

Organic farming eliminates synthetic fertilizers and pesticides while emphasizing organic amendments, crop rotations, and residue incorporation, practices that can enhance SOC by increasing organic inputs and enhancing soil biodiversity (Bumb *et al.*, 2021). However, studies reported that these benefits may be associated with higher CH_4 emissions, particularly in flooded rice systems where organic amendments are utilized as substrates for methanogens (Swain *et al.*, 2023). For example, CH_4 emissions were significantly higher in organic plots than in conventional systems, highlighting that the gains in SOC may be offset by higher CH_4 fluxes (Song *et al.*, 2024). This practice highlights a critical trade-off between the buildup of SOC on account of the reduction of synthetic fertilizers application and the increase of CH_4 due to higher substrate availability. However, the positive outcomes of organic farming depend on several factors, such as soil type, water management, and soil amendment.

Alternate Wetting and Drying (AWD)

Alternate wetting and drying (AWD) is promoted as a climate-smart water management practice in rice systems. The AWD techniques reduce anaerobic conditions and significantly decrease CH_4 emissions compared to continuous flooding (Nair *et al.*, 2022). However, AWD can enhance nitrification and denitrification, often resulting in increased N_2O emissions. This trade-offs between the reduction in CH_4 may be partially offset by increase in N_2O emissions (Nordahl *et al.*, 2023). In addition, AWD can alter soil redox conditions, influencing nutrient availability, root health, and microbial activity, which may affect yields under various soil types or climate conditions (Vending *et al.*, 2023). Integrating AWD with complementary practices such as optimized fertilizer management, mid-season drainage, or organic amendments can help minimize N_2O losses while retaining the water-saving and climate mitigation benefits of AWD.

Residue Management

Residue management, which involves retaining, incorporating, or partially removing crop residues after harvest, plays an important role in influencing SOC dynamics and GHGs emissions. Parida *et al.* (2025) suggested that incorporating crop residues into soils can enhance SOC accumulation by providing additional organic substrates that contribute to soil carbon pools and improve soil structure, water retention, and nutrient cycling. For example, a simulation study of rice fields in China showed that incorporating rice straw could increase soil carbon stocks from 21.8 to 23.9 Mg ha^{-1}, with soil carbon sequestration rates rising to 24.4 Tg C yr^{-1} (Chen *et al.*, 2019). However, the organic substrates that promote SOC accumulation can also enhance microbial decomposition, creating conditions favourable for CH_4 and N_2O production, but under anaerobic and alternate wetting and drying conditions (Lehtinen *et al.*, 2014). Strategies to mitigate these emissions include pretreating residues with in-situ microbial culture, converting to biochar before soil application. These have been shown to reduce CH_4 emissions relative to direct incorporation of fresh residues to soil (Chareonsilp *et al.*, 2000). However, residue management represents the trade-off between SOC-GHGs in regenerative agriculture. While proper management can enhance SOC storage, it may simultaneously increase GHGs emissions if decomposition pathways are not managed properly. Optimizing residue management practices, including timing, method of incorporation, and treatment of residues can help to balance SOC gains with minimized GHGs emissions. The reported impacts of major regenerative agriculture practices on SOC and GHGs emissions are summarized in Figure 3.

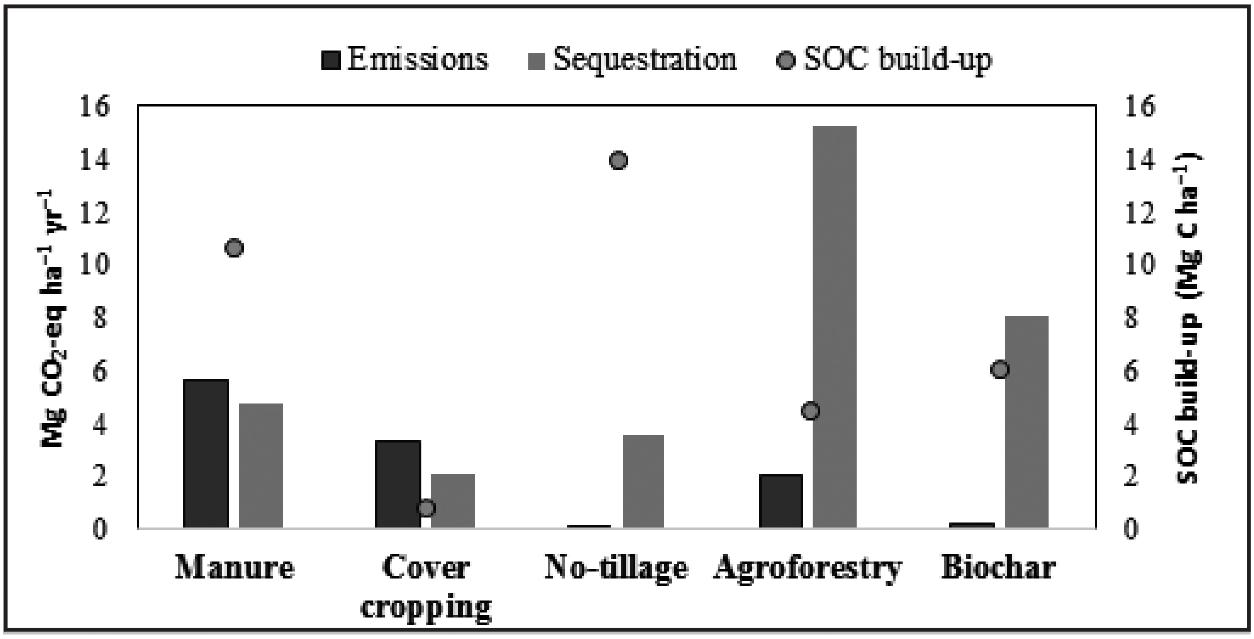

Figure 3. Greenhouse gases (GHGs) emissions and CO_2 sequestration (Mg CO_2 ha^{-1} yr^{-1}) associated with different land management practices, with corresponding soil organic carbon (SOC) build-up (Mg C ha^{-1}) shown on the secondary axis.

Limitations and Future Research

Although regenerative agriculture (RA) has been globally promoted for its positive effects on SOC and the reduction of GHGs emissions, on-field implementation involves several challenges and limitations. The SOC measurement techniques vary widely, including Walkley-Black, dry combustion, and humic matter extraction, each differing in carbon recovery rates and precision. In tropical soils, these differences can lead to over or underestimation of SOC stocks. Additionally, changes in soil bulk density due to tillage, residue incorporation, or organic amendments could influence SOC estimations. Most studies also focus on shallow soil layers (0-30 cm), while RA effects often extend deeper, potentially underestimating long-term carbon storage. Addressing these methodological challenges through standardized measurement protocols, bulk density corrections, and deep soil sampling would improve the reliability of SOC assessments and the evaluation of climate benefits from RA practices.

Another key limitation is the focus on single interventions, whereas farmers often implement multiple RA practices simultaneously. Hybrid approaches, such as cover cropping combined with no-tillage or biochar amendments with organic fertilization, may lead to synergistic effects on SOC build-up and GHGs emissions mitigation. Future research should focus on multi-practice interactions, quantify both SOC and GHGs trade-offs, and systematically assess the co-benefits of RA strategies for ecosystem services.

Conclusion

Regenerative agriculture (RA) offers a promising pathway to enhance soil carbon storage and mitigate climate change, but its benefits involve the trade-offs between SOC buildup and GHGs emissions. Practices such as agroforestry, biochar application, composting, cover cropping, manure use, improved seed varieties, crop rotation, residue management, and organic farming generally increase soil organic carbon (SOC) through enhanced biomass inputs, root development, and improved soil structure. These gains, however, may be offset by increased greenhouse gas emissions, particularly CH_4 and N_2O, arising from organic amendments, residue decomposition, or nitrogen-rich plant inputs. The net balance of these trade-offs are significantly influenced by factors including soil type, climate, management practices, amendment properties, and the method of SOC measurement. Integrated strategies, such as combining biochar with organic amendments or adopting crop rotations with minimal tillage, have the potential to enhance carbon storage while mitigating emissions. Moreover, considering co-benefits such as improved soil fertility, crop yields, and ecosystem resilience is necessary to fully evaluate the value (tangible and intangible) of RA practices. By addressing these knowledge gaps and implementing specific management strategies, RA can serve as a robust tool for sustainable agriculture, climate change mitigation, and long-term soil health improvement.

Acknowledgement

Authors acknowledge the support of NICRA (EAP-245), NASF (EAP-411) for providing support to conduct the literature review and research works. Authors are grateful to Director of ICAR-CRRI, for his support and guidance. Authors are acknowledged the help and support provided Mr. Saroj Kumar Rout, Mr. Jiten Kumar Sahu, Mr. Gaban Mandi for their support and help.

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