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N Sravya
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University,
Thiruvananthapuram, Kerala, India

Jagmal P Khatana
M.Sc. Scholar, Department of Agronomy,
Chimanbhai Patel College of Agriculture,
Sardarkrushinagar Dantiwada Agricultural
University, Dantiwada, Gujarat, India

V Siva Teja
Ph.D. Scholar, Department of Floriculture
and Landscaping, College of Agriculture,
Vellanikkara, Kerala Agricultural
University, Thrissur, Kerala, India

Deshmukh Sarita Babarao
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University,
Thiruvananthapuram, Kerala, India

Harshavardhan Mohan Totawar
Ph.D. Scholar, Department of Vegetable
Science, College of Agriculture, Vellayani,
Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

Laxmi PS
Ph.D. Scholar, Department of Postharvest
Management, College of Agriculture,
Vellanikkara, Kerala Agricultural
University, Thrissur, Kerala, India

Sruthi T
Ph.D. Scholar, Department of Genetics and
Plant Breeding, College of Agriculture,
Vellayani, Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

Khushal B Muradi
Ph.D. Scholar, Department of Vegetable
Science, College of Agriculture,
Vellanikkara, Kerala Agricultural
University, Thrissur, Kerala, India

Yogesh V Wayal
Ph.D. Scholar, Department of Genetics and
Plant Breeding, College of Agriculture,
Vellayani, Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

Choudhari Balaji Keshavrao
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University,
Thiruvananthapuram, Kerala, India

Corresponding Author:
N Sravya
Ph.D. Scholar, Department of Agronomy,
College of Agriculture, Vellayani, Kerala
Agricultural University,
Thiruvananthapuram, Kerala, India

Enhancing soil carbon sequestration through sustainable agronomic and land-use practices

**N Sravya, Jagmal P Khatana, V Siva Teja, Deshmukh Sarita Babarao,
Harshavardhan Mohan Totawar, Laxmi PS, Sruthi T, Khushal B Muradi,
Yogesh V Wayal and Choudhari Balaji Keshavrao**

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Abstract

The rising concentration of atmospheric carbon dioxide (CO₂) and other greenhouse gases since the industrial revolution has significantly contributed to global climate change. Within the agricultural sector, soil carbon sequestration represents the most effective mitigation option, accounting for nearly 90% of the technically feasible potential. The review emphasizes soil and land-use management practices such as conservation tillage, integrated nutrient management, residue retention, biochar application, agroforestry, and diversified cropping systems that enhance soil organic carbon storage.

Keywords: Soil carbon sequestration, climate change mitigation, sustainable agriculture, land-use management

Introduction

The continuous rise in atmospheric carbon dioxide (CO₂) and other greenhouse gases (GHGs) since the industrial revolution is widely recognized as a major driver of global climate change and its associated environmental consequences. Among the various mitigation options available within the agricultural sector, soil carbon sequestration at the global scale is considered to have the greatest potential, contributing nearly 90% of the technically feasible mitigation capacity. Carbon fixation through photosynthesis represents a natural mechanism for removing CO₂ from the atmosphere, whereby carbon is converted into organic forms that do not contribute to global warming. This process is referred to as carbon sequestration.

Carbon sequestration involves the capture and long-term storage of carbon in stable reservoirs. For effective mitigation, the stored carbon must be deposited in long-lasting pools such as oceans, geological formations, chemical compounds, and terrestrial ecosystems. Therefore, the adoption of improved agronomic and land management practices that reduce carbon losses or enhance soil carbon storage is of considerable importance.

Sources of Carbon Dioxide Emissions

Carbon dioxide emissions arise from both natural processes and anthropogenic activities; however, human activities are the dominant contributors to contemporary climate change. The combustion of fossil fuels such as coal, oil, and natural gas, along with deforestation, has significantly increased atmospheric CO₂ concentrations. Approximately 87% of anthropogenic CO₂ emissions originate from fossil fuel burning, while about 9% result from land-use changes, including forest clearing. The remaining 4% is attributed to industrial processes, particularly cement production.

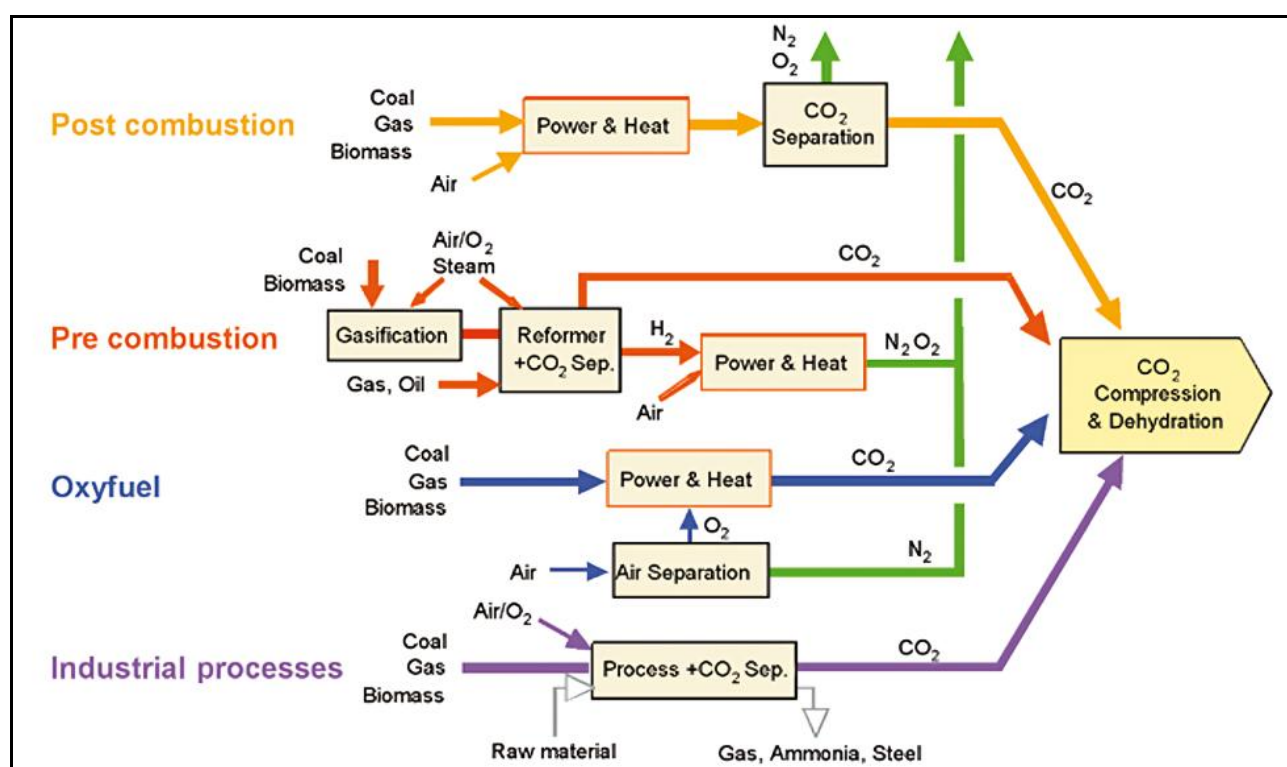
Global carbon dioxide emissions from fossil fuel consumption in the year 2000 were approximately 23.5 GtCO₂ per year (equivalent to about 6 GtC per year). Nearly 60% of these emissions originated from large stationary sources emitting more than 0.1 MtCO₂ annually, although only a portion of these sources are technically suitable for CO₂ capture. While such emission sources are distributed worldwide, four major regional concentrations can be identified: the midwestern and eastern regions of the United States, northwestern Europe, the

eastern coastal areas of China, and the Indian subcontinent. In contrast, large-scale biomass-based emission sources are relatively few and unevenly distributed globally. According to the IPCC Special Report on Emission Scenarios (SRES), future global CO₂ emissions are projected to range between 29 and 44 GtCO₂ per year by 2020, and between 23 and 84 GtCO₂ per year by 2050, depending on the scenario considered. The number of emission sources from the power generation and industrial sectors is expected to increase substantially up to 2050, particularly in South and East Asia, while a slight decline is anticipated in Europe. The proportion of emission sources with high or low CO₂ concentrations will depend on the extent to which technologies such as fossil fuel gasification or liquefaction are adopted for the production of hydrogen and other energy carriers. A greater deployment of these technologies would increase the number of sources with CO₂ concentrations suitable for capture. Based on these projections, the potential amount of CO₂ that could be captured is estimated to be between 2.6 and 4.9 GtCO₂ per year by 2020 and between 4.7 and 37.5 GtCO₂ per year by 2050, corresponding to approximately 9-12% and 21-45% of total global CO₂ emissions, respectively. Reports from the International Energy Agency (2016) and NASA (2017) indicate that atmospheric carbon dioxide concentrations increased from about 280 ppm in the mid-nineteenth century to nearly 404 ppm by 2016, leading to an approximate 1 °C rise in global mean surface temperature relative to pre-industrial conditions. This warming, observed over the period from 1901 to 2010, contributed to a global average sea-level rise of around 20 cm (UK Met Office, 2016). It is now broadly recognized that limiting the increase in global average temperature to well below 2 °C above pre-industrial levels by the end of the twenty-first century is essential to prevent severe climate-related impacts. In response to this challenge, the European Union and G7 nations have committed to reducing greenhouse gas emissions by at least 80% compared to 1990 levels by 2050 (ECF Roadmap).

There are three principal technological pathways for capturing

CO₂ produced from the use of fossil fuels, biomass, or their combinations.

- 1. Post-combustion capture systems:** In post-combustion capture systems, CO₂ is separated from flue gases generated during fuel combustion in air. These flue gases typically contain a relatively low concentration of CO₂, usually between 3 and 15% by volume, with nitrogen as the dominant component. Current post-combustion technologies commonly employ liquid chemical solvents, such as monoethanolamine, particularly in pulverized coal and natural gas combined cycle power plants.
- 2. Pre-combustion capture systems:** In pre-combustion capture systems, the primary fuel is first converted into synthesis gas through reaction with steam and air or oxygen. This gas, consisting mainly of carbon monoxide and hydrogen, is further processed in a shift reactor where carbon monoxide reacts with steam to produce additional hydrogen and CO₂. The resulting gas mixture is then separated into a CO₂ stream and a hydrogen-rich stream, with the hydrogen serving as a carbon-free energy carrier. Although pre-combustion systems involve more complex and costly fuel processing steps, they benefit from higher CO₂ concentrations and elevated pressures, which facilitate separation. This approach is typically associated with integrated gasification combined cycle power plants.
- 3. Oxyfuel combustion:** Oxyfuel combustion represents a third approach, in which fuel is burned in nearly pure oxygen rather than air, producing a flue gas composed primarily of CO₂ and water vapour. After condensation of the water vapour, a highly concentrated CO₂ stream remains. This technology requires prior oxygen separation from air and additional flue gas treatment to remove impurities. Oxyfuel combustion systems for boilers are currently at the demonstration stage, while their application in gas turbine systems remains under active research and development.



Overview of CO₂ capture processes and systems (Li *et al.*, 2013) ^[25]

Methods of Carbon Sequestration

Carbon can be sequestered through two major approaches: non-biological and biological sequestration methods.

Non-Biological Carbon Sequestration

Non-biological carbon sequestration involves the capture and storage of atmospheric CO₂ through physical and chemical processes without the involvement of living organisms. This approach includes oceanic, geological, and chemical sequestration techniques.

Oceanic sequestration exploits the large capacity of oceans as carbon sinks, as the oceanic inorganic carbon pool is nearly 50 times greater than that of the atmosphere. Oceanic sequestration can be categorized into abiotic and biotic processes. Abiotic sequestration involves the direct injection of CO₂ into deep ocean waters, whereas biotic sequestration enhances carbon capture through biological activity in coastal ecosystems.

Geological sequestration involves the storage of CO₂ in underground formations such as depleted oil and gas reservoirs, coal seams, and deep saline aquifers. Injected CO₂ can be utilized to enhance oil recovery while simultaneously reducing greenhouse gas emissions. In saline aquifers, CO₂ is stored in a supercritical state, where it dissolves in brine or reacts with surrounding minerals.

Chemical sequestration primarily occurs through mineral carbonation, a process in which CO₂ reacts with metal oxides present in rocks to form stable carbonate minerals. These carbonates can store carbon over geological time scales. Although the efficiency of industrial mineral carbonation is currently low, natural mineral carbonation occurs continuously and has potential for commercial application.

Biological Carbon Sequestration

Biological carbon sequestration involves the accumulation and long-term retention of carbon by plants and microorganisms through natural biological processes. This method mainly includes ocean fertilization and terrestrial sequestration.

Ocean fertilization enhances carbon sequestration by stimulating phytoplankton growth through the addition of nutrients such as iron. Increased phytoplankton productivity leads to enhanced photosynthetic carbon capture, thereby increasing carbon sequestration in marine systems.

Terrestrial sequestration refers to the storage of carbon in plant biomass and soils, both above and below ground. Carbon is sequestered through phyto-sequestration and soil carbon sequestration processes. Soil carbon storage is influenced by several factors, including climate, rainfall, temperature, soil texture, clay content, and management practices.

Overall, biological carbon sequestration through agricultural and forestry practices plays a crucial role in removing CO₂ from the atmosphere and storing it within terrestrial ecosystems for extended periods (Mishra *et al.*, 2022) ^[15].

Options for mitigating climate change

The UN Framework Convention on Climate Change aims to stabilize greenhouse gas concentrations by balancing anthropogenic emissions with natural removal processes. Lower stabilization targets such as 450 ppm CO₂ require earlier and deeper emission reductions than higher targets. Studies show that stabilization at 550 ppm may need 7-70% emission cuts by 2100, while 450 ppm could require reductions of 55-90%. Future emissions are strongly influenced by population growth, economic development, energy intensity, and carbon intensity. Therefore, achieving climate stabilization depends on

widespread adoption of cleaner and cost-effective energy technologies.

- 1. Improve Energy Efficiency:** Improving energy efficiency is one of the most effective options for mitigating climate change, as it directly reduces fossil fuel consumption by enhancing energy conversion, transport, and end-use efficiency. Advances in electricity generation, such as improved turbines and combined heat, cooling, and power (CHP) systems, have significantly lowered CO₂ emissions. Since 1970, technological improvements have achieved reductions of two to four times in the energy consumption of vehicles, lighting systems, and household appliances. Both demand-side and supply-side efficiency measures offer substantial near-term mitigation potential and can slow the growth of greenhouse gas emissions into the future. Many of these measures can be implemented at low or even negative economic cost. However, despite their large potential, energy efficiency improvements alone are unlikely to be sufficient to achieve deep, long-term reductions in greenhouse gas emissions.
- 2. Switch to Less Carbon-Intensive Fossil Fuels:** Switching from high-carbon fossil fuels such as coal to lower-carbon fuels like natural gas is a cost-effective mitigation option where suitable supplies are available. In electricity generation, replacing coal with natural gas can reduce emissions by about 420 kg CO₂ per MWh, equivalent to nearly a 50% reduction. When combined with the co-production of heat, cooling, and electricity, emission reductions can be even greater. This option can make a substantial contribution to emissions reduction at individual power plants. However, its wider application is limited by the availability of natural gas supplies and supporting infrastructure. Fuel transport constraints and regional resource distribution further affect feasibility. As a result, fuel switching is mainly considered a transitional mitigation strategy rather than a long-term solution.
- 3. Increased Use of Low- and Near-Zero-Carbon Energy Sources:** Deep reductions in greenhouse gas emissions from stationary sources can be achieved by increasing the use of renewable energy and nuclear power. The extent of nuclear power deployment is largely influenced by political processes, public opinion, and concerns related to cost, safety, waste management, and security rather than technical limitations. Renewable energy sources, including wind, solar, biomass, hydro, geothermal, and tidal power, offer significant potential to displace fossil fuels in electricity generation, transport fuels, and heating and cooling applications. Rapid growth in wind and solar power has been driven by falling costs and supportive policies. Biomass energy provides additional co-benefits such as rural employment and energy security. However, challenges such as intermittency, land use requirements, high initial costs, and environmental impacts limit the extent of large-scale deployment and vary by geographic location.
- 4. Sequester CO₂ through Enhancement of Natural, Biological Sinks:** Natural biological sinks such as forests and soils already play a significant role in regulating atmospheric CO₂ concentrations. These sinks can be enhanced through improved agricultural and forestry practices to increase carbon uptake and storage. Biological sequestration has the potential to offset a considerable portion of anthropogenic CO₂ emissions. However, large-scale enhancement is constrained by land availability and competing land-use demands. Social and environmental

factors also influence the adoption of sequestration practices. In addition, carbon stored in biological systems may not be permanent, as it can be released through land-use change or natural disturbances. Despite these limitations, biological sequestration is considered a promising and low-cost near-term mitigation option.

5. **CO₂ Capture and Storage (CCS):** CO₂ capture and storage involves capturing carbon dioxide from large industrial sources and power plants and storing it in geological formations such as depleted oil and gas fields or deep saline aquifers. CCS is most suitable for large, centralized emission sources rather than small, dispersed emitters. While the technology has significant mitigation potential, the capture process requires additional energy, leading to increased fuel consumption and associated emissions. The feasibility of CCS depends on factors such as cost, long-term storage security, transport infrastructure, environmental risks, and public acceptance. A particularly promising development is the combination of biomass energy with CCS, which can result in net negative CO₂

emissions. Although CCS was initially considered to have modest near-term potential, it is now recognized as an important long-term mitigation option, especially beyond 2020.

6. **Potential for Reducing CO₂ Emissions:** Assessments indicate that the global application of technological mitigation options could reduce greenhouse gas emissions by approximately 25-40% in the short term, with substantially higher potential by 2020 and beyond. Among available options, energy efficiency improvements offer the largest near-term reduction potential. Early assessments suggested limited contributions from CCS, but more recent analyses recognize a much larger potential. However, these estimates are subject to uncertainty due to reliance on data from the 1990s and the absence of comprehensive global studies. Regional and national estimates vary widely because of differing assumptions, resource availability, and policy frameworks. Achieving long-term climate goals will therefore require the combined implementation of multiple mitigation strategies.

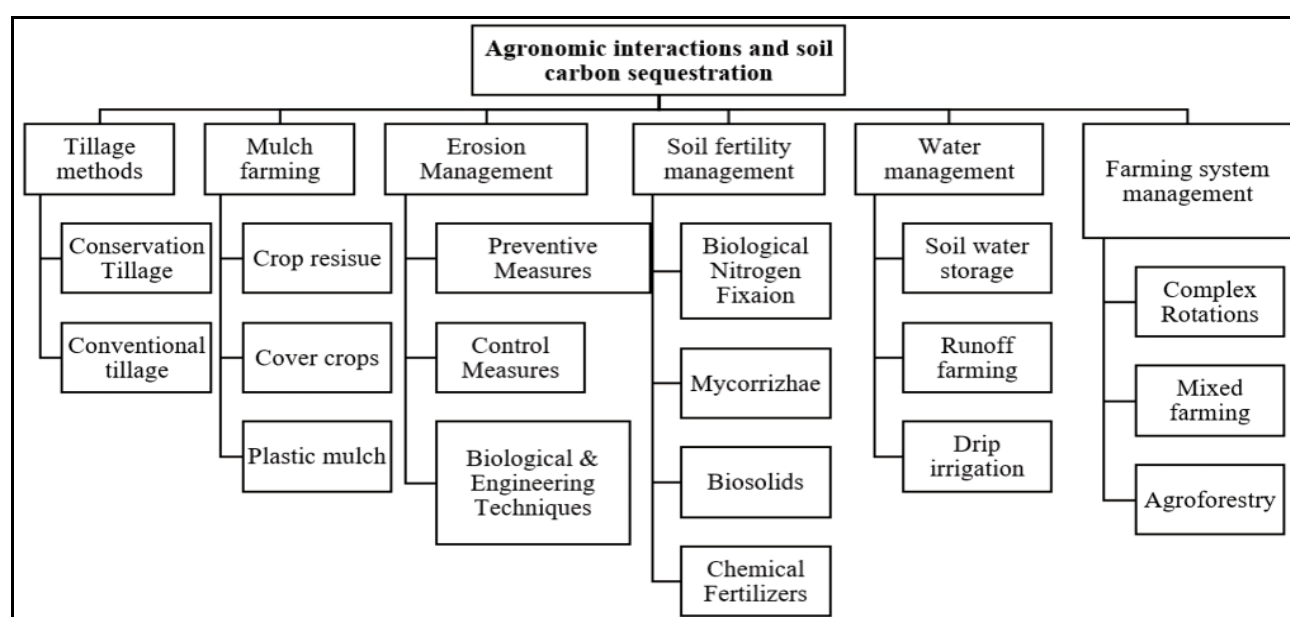


Fig 1: Conceptual flow diagram illustrating agronomic management strategies designed to promote soil carbon sequestration (Leno, 2020) ^[14].

Approaches for Improving Soil Carbon Sequestration

Laser Land Levelling: Laser land levelling has been identified as an important agronomic practice for improving soil carbon sequestration. Laser land levelling (LLL) is a precision agricultural technique that uses laser-guided technology to create a flat or consistently sloped (0 to 0.2%) soil surface. It works by using a tractor-mounted drag bucket to automatically cut soil from high points and deposit it in low points, typically within ± 2 cm of accuracy. By ensuring uniform land surface and improved water distribution efficiency, laser land levelling enhances crop growth and residue production, which indirectly contributes to greater carbon inputs to soil and improved soil organic carbon (SOC) storage (Jat *et al.*, 2022) ^[10].

Tillage Practices: Soil tillage is one of the major factors influencing soil organic carbon dynamics, as intensive tillage accelerates SOC loss by increasing soil disturbance and organic matter oxidation. Adoption of zero tillage or reduced tillage practices promotes SOC sequestration and is widely recognized as a key global climate change mitigation strategy. Zero tillage has been consistently reported as an effective practice for

enhancing soil carbon storage, particularly in surface soil layers. Long-term studies have shown that the highest rate of carbon sequestration occurs under no tillage systems. An increase of $571 \text{ kg C ha}^{-1} \text{ year}^{-1}$ was recorded under no tillage from 1995 to 2024, followed by reduced tillage ($462 \text{ kg C ha}^{-1} \text{ year}^{-1}$) and conventional tillage ($221 \text{ kg C ha}^{-1} \text{ year}^{-1}$). The SOC content increased gradually throughout the soil profile (0-30 cm), with significantly higher accumulation under conservation tillage systems (Muhlbachova *et al.*, 2025) ^[16].

Reduced and zero tillage practices promote the stabilization of soil aggregates, which physically protect organic carbon from microbial mineralization. Reduced tillage maintained 1.29% SOC, whereas conventional tillage maintained only 1.22% SOC after two years of experimentation (Sudha *et al.*, 2011) ^[22]. Similarly, Kushwa *et al.* (2016) ^[13] reported higher SOC levels under no tillage (8.8 g kg^{-1}), followed by reduced tillage (7.9 g kg^{-1}), mouldboard ploughing (6.9 g kg^{-1}), and the lowest SOC under conventional tillage (5.9 g kg^{-1}).

The increase in SOC under conservation tillage systems is attributed to the retention of crop residues on the soil surface and reduced soil disturbance. Additionally, organic matter below the

soil surface, including root biomass from previous crops, remains undisturbed and decomposes more slowly due to reduced oxidation under conservation tillage, thereby enhancing SOC accumulation.

Integrated Nutrient Management: Integrated nutrient management plays a crucial role in improving soil organic carbon stocks by enhancing organic matter inputs and soil biological activity. Application of organic manures such as farmyard manure (FYM), poultry manure, goat manure, pig manure, vermicompost, and biochar has been shown to alleviate SOC deterioration and enhance carbon sequestration.

Application of organic manures and biochar in maize-black gram cropping systems significantly improved carbon sequestration potential and enhanced soil carbon fractions compared to control treatments without organic amendments (Das *et al.*, 2024) ^[4]. Combined application of chemical fertilizers and organic manures increased SOC contents by 30-45% and enhanced carbon sequestration rates by 7.1-9.0 times compared to fertilizer-only treatments (Sui *et al.*, 2017) ^[23].

Among different nutrient management practices, significantly higher SOC stocks and carbon sequestration rates in the 0-15 cm soil layer was observed under the application of 100% recommended dose of fertilizers (RDF) combined with FYM and ZnSO₄ compared to fertilizer-alone treatments (Goutami, 2025) ^[7]. Similarly, integrated use of fertilizers and organic amendments improved soil quality and enhanced soil carbon sequestration in rice-wheat cropping systems of the Indo-Gangetic plains (Ghosh *et al.*, 2012) ^[6].

Kumar and Maheswarappa (2019) ^[20] reported the highest SOC content under integrated nutrient application involving FYM, partial substitution of chemical fertilizers with vermicompost and composted coir pith, along with micronutrient supplementation, compared to inorganic fertilizers alone. Furthermore, permanent bed systems combined with site-specific nutrient management (SSNM) recorded 44.1% higher SOC content compared to unfertilized conventional tillage systems (Parihar *et al.*, 2020) ^[19].

Mulch Farming: Mulch farming and the use of cover crops enhance soil carbon sequestration by increasing biomass inputs and reducing carbon losses. Crop residues, which remain in the field after harvesting and threshing, serve as valuable organic inputs that contribute to soil carbon accumulation. Effective recycling of crop residues, either as surface mulch or through incorporation into soil, has a significant influence on SOC dynamics.

Surface mulching maintains higher SOC and soil organic matter (SOM) levels in the upper soil layers, whereas incorporation of residues improves SOC and SOM content in deeper soil layers by placing organic material directly into the subsurface soil (Sudha *et al.*, 2007) ^[22]. Soil carbon primarily originates from organic matter, and an increase in soil organic matter improves soil water-holding capacity and enhances crop resilience under drought conditions.

Biochar Application: The Intergovernmental Panel on Climate Change (IPCC) emphasizes the need for carbon-negative practices in the 21st century to mitigate the adverse effects of climate change. Biochar application represents an effective strategy for achieving this goal by converting biomass carbon into a stable and recalcitrant form through pyrolysis and using it as a soil amendment.

The carbon sequestration potential of biochar is well illustrated by Terra Preta soils of the Amazon Basin, which contain large quantities of low-temperature charcoal residues that have persisted for hundreds of years. These soils exhibit enhanced nutrient retention and reduced nutrient leaching, highlighting the long-term stability of biochar-derived carbon.

Conversion of biomass carbon into biochar enables sequestration of nearly 50% of the initial biomass carbon, whereas only about 3% of carbon is retained when biomass is directly burned. Biochar carbon is highly resistant to microbial degradation and has a long residence time in soil, making it an effective long-term carbon sink.

Biochar application enhances soil fertility and contributes to sustained carbon storage. Incorporation of paddy husk biochar and coconut frond biochar significantly reduced CO₂ emissions from soil compared to FYM application (Jabin *et al.*, 2023) ^[9]. Biochar also reduces soil organic matter degradation and neutralizes CO₂ emissions due to its chemical stability. Owing to its recalcitrant nature, converting biomass into biochar prior to soil application is more effective for increasing soil carbon storage than direct biomass incorporation. Studies have also reported substantially lower CO₂ emissions from paddy soils following biochar application.

Agroforestry: Agroforestry refers to the deliberate integration of trees and shrubs with agricultural crops and/or livestock systems to generate environmental, economic, and social benefits. This land-use system is recognized as an effective strategy for enhancing soil carbon sequestration and mitigating climate change impacts, and it is included under the Clean Development Mechanism of the Kyoto Protocol.

Trees in agroforestry systems function as significant carbon sinks by fixing atmospheric CO₂ through photosynthesis and storing carbon in above- and below-ground biomass. The role of forests and tree-based systems as carbon sources or sinks varies over time, depending on growth, mortality, and decomposition processes. Among land management practices, reforestation, natural regeneration, and agroforestry have been identified as the most promising options for long-term CO₂ mitigation (Chaudhari *et al.*, 2015) ^[2].

Agroforestry practices such as alley cropping and shelterbelts strongly influence soil organic matter (SOM) quantity, quality, and composition. The incorporation of tree components alters litter quality and decomposition dynamics, thereby affecting SOM formation. In alley-cropping systems, diversity in root distribution, biomass, and functional traits results in variable contributions of root-derived carbon to soil. Root inputs through rhizodeposition and root turnover play a critical role in soil carbon storage, as the recalcitrant nature of root residues slows decomposition and promotes the formation of stable SOM. Root-derived carbon inputs have been reported to contribute 2-5 times more to stable soil organic matter formation than aboveground plant residues.

In addition to direct soil carbon storage, agroforestry biomass contributes to climate change mitigation by offsetting fossil fuel consumption, thereby reducing atmospheric CO₂ concentrations. The Intergovernmental Panel on Climate Change (IPCC) recognizes agroforestry as one of the most effective land-use systems for carbon sequestration. Agroforestry also forms a key component of global initiatives such as Reducing Emissions from Deforestation and Forest Degradation, supporting both climate change mitigation and adaptation.

Long-term field studies have demonstrated substantial improvements in soil carbon under agroforestry systems. A

mulberry-based agroforestry system (mulberry + cowpea-toria) recorded 58% higher total SOC than cultivated fallow land after 15 years in the 0-15 cm soil layer in the Himalayan region (Barman, 2025) ^[1]. Among commonly used agroforestry tree species, *Quercus leucotrichophora*, *Melia azedarach*, and *Prunus cerasoides* exhibited the highest carbon storage potential. Overall, agroforestry systems showed higher SOC content and lower soil bulk density compared to sole cropping systems (Kumar *et al.*, 2025) ^[12].

Similarly, soil organic carbon under four-year-old *Populus* and *Eucalyptus*-based agroforestry systems was 22.9% and 6.3% higher, respectively, than under sole wheat cultivation. Increased SOC in subsoil layers was attributed to organic matter inputs from fine and coarse roots and their rapid turnover, while enhanced surface SOC resulted from higher carbon inputs through litter fall, dead roots, and root exudates.

Cropping Systems: Carbon sequestration rate (CSR) refers to the process by which atmospheric carbon is captured and stored in soil over long periods. Cropping systems play a critical role in regulating CSR by influencing biomass input, residue management, and soil disturbance. Diverse and residue-rich cropping systems enhance soil organic matter accumulation and improve the stabilization of carbon in soil.

Studies have shown that conservation-based cropping systems combined with residue retention significantly enhance carbon sequestration. Nthebere *et al.* (2025) ^[17] reported the highest cumulative CSR under zero tillage systems integrated with crop residues, including cotton + *Sesbania rostrata* residues, maize + cotton residues, and *Sesbania rostrata* + maize stubbles. The enhanced carbon sequestration under these systems was attributed to minimal soil disturbance, improved soil aggregate stability, and increased soil organic matter resulting from permanent soil cover and diversified residue inputs, which promote rapid turnover of the active carbon pool.

Cropping system diversification also enhances carbon stock and CO₂ sequestration compared to monocropping systems. In coconut-based systems, plots under intercropping recorded significantly higher carbon stocks and CO₂ sequestration than monocropped coconut, owing to additional biomass inputs from intercrops (Shinde *et al.*, 2020) ^[20]. Trees function as major carbon reservoirs, and forest ecosystems play a crucial role in the global carbon cycle by storing large quantities of carbon and regulating atmospheric CO₂ through continuous exchange processes (Chavan and Rasal, 2012) ^[3].

The coconut agro-ecosystem is an important plantation-based agricultural system that provides food, shelter, and ecological services. Since trees account for nearly 75% of the Earth's biomass, understanding the long-term carbon sequestration potential of plantation systems is essential for climate change mitigation. During the post-experimental period, coconut under intercropping systems sequestered 16.13 t ha⁻¹ of carbon, compared to 14.48 t ha⁻¹ under monocropping, indicating the superiority of diversified cropping systems for carbon storage (Kumar and Maheswarappa, 2019) ^[11].

Enhanced soil organic carbon accumulation has also been observed in coconut-based intercropping systems. Sudha and George (2011) ^[22] reported improved SOC status under coconut + pineapple systems, primarily due to the recycling of lignin-rich pineapple residues into the soil. The slow decomposition of these residues increased soil organic matter levels, thereby improving SOC content.

Conservation agriculture (CA)-based diversified cropping systems have demonstrated substantial gains in SOC. The SOC

content increased by 72% under maize-wheat-mung bean and by 83% under rice-wheat-mung bean systems compared to the conventional rice-wheat system (Parihar *et al.*, 2018) ^[18]. Similarly, Singh and Lal (2011) ^[21] observed higher organic carbon and nutrient availability in legume-integrated systems, where the inclusion of greengram in potato-based cropping increased SOC compared to non-legume systems. The incorporation of greengram residues during rice puddling contributed to increased soil organic matter through decomposition.

Long-term diversified cropping has also been shown to improve soil carbon sequestration even with reduced fertilizer inputs. A six-year diversified cropping system enhanced topsoil carbon sequestration despite a 40% reduction in nitrogen fertilizer compared to wheat-maize systems. This improvement was largely attributed to increased inputs of senescent roots and legume nodules, which contributed significantly to SOC accumulation (Yan *et al.*, 2023) ^[24].

Conclusion

Soil carbon sequestration represents a viable and sustainable strategy for mitigating climate change while enhancing soil quality and agricultural resilience. The integration of sustainable land-use practices and diversified cropping systems offers a synergistic approach to maximizing soil carbon sequestration. Adoption of these practices at larger scales can contribute significantly to reducing atmospheric CO₂ concentrations while improving soil fertility, water-holding capacity, and long-term agricultural sustainability. Strengthening policy support and promoting farmer adoption of such climate-smart practices will be crucial for achieving long-term mitigation and adaptation goals.

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