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Carbon farming: Innovations, potential, and challenges for sustainable future

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ABSTRACT

Carbon farming refers to agricultural practices aimed at reducing greenhouse gas (GHG) emissions and enhancing carbon sequestration in soils and vegetation, thus contributing to climate change mitigation. Key practices such as agroforestry, conservation tillage, biochar application, and improved crop and livestock management helps in sequestering carbon in both biomass and soil, offering substantial potential for capturing atmospheric carbon dioxide (CO_2) and storing it in agricultural landscapes. Despite the considerable promise of carbon farming, its widespread adoption faces challenges, including the impacts of climate change, as well as limited access to resources, knowledge, and markets, particularly in developing countries like India. Nonetheless, carbon farming provides multiple co-benefits, such as enhanced soil health, increased biodiversity, improved agricultural productivity, and greater resilience to climate extremes. In India, carbon markets and public subsidies are key drivers, incentivizing farmers to adopt carbon farming practices by offering soil carbon certificates. India's carbon stock has reached 30.43 billion tonnes of CO_2 equivalent, indicating that the country has already achieved 2.29 billion tonnes of additional carbon sequestration compared to the 2005 baseline, approaching its target of 2.5 to 3.0 billion tonnes by 2030. Furthermore, important government initiatives such as climate action plans, net-zero goals, de-carbonization, green hydrogen development, and carbon capture utilization and storage (CCUS) play a significant role in advancing sustainable carbon management. This article examines the global potential of carbon farming, with a particular focus on India, exploring its impact on carbon storage, the role of various practices, and the challenges involved in it promotion and adoption.

Key word: Carbon farming, Climate change, Environment, Soil carbon sequestration

Agricultural activities are responsible for a substantial share of global greenhouse gas (GHG) emissions, further intensifying climate change. The primary GHGs emitted from agriculture are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2).

Methane is primarily released through enteric fermentation in livestock and rice cultivation in flooded fields (FAO, 2017). Nitrous oxide emissions largely arise from the use of nitrogen fertilizers in crop production, which have a global warming potential far greater than CO_2 (IPCC, 2021). Agricultural expansion, including deforestation and land-use changes, releases large amounts of carbon stored in trees and soils, exacerbating climate change (IPCC, 2007). Thus, traditional agriculture acts both as a victim of and a contributor to climate change, which complicates the relationship between farming systems and climate dynamics (Avasthe *et al.,* 2023; Dhillon. and Sohu, 2024).

Fossil fuel-based energy accounts for ~ 84% of global energy consumption, significantly increasing atmospheric CO_2 levels, which have risen from ~280 ppm before the Industrial Revolution to over 417 ppm in 2024 (Olim *et al.,* 2025). This rise in CO_2 is a major driver of global warming, contributing to 26% of the overall increase in global temperatures (Bhui, 2021). Despite efforts to reduce emissions, fossil fuels continue to dominate global energy consumption, with global energy use projected to double by 2030, mainly driven by fossil fuels (Lau *et al.,* 2021). This could lead to a 2°C temperature rise by 2065, surpassing the IPCC's target of limiting global warming to 2°C by 2100 (Lau *et al.,* 2021). The Paris Agreement aims to limit global warming to well below 2°C by 2100, with emissions reductions of 50-80% from 1990 levels by 2050 (Bui *et al.,* 2018). The challenge of reducing CO_2 emissions presents significant implications for environmental

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sustainability. Effective carbon sequestration strategies, such as carbon capture and storage (CCS), offer potential solutions for reducing CO_2 emissions. Biological carbon sequestration through photosynthesis in plants, along with the use of biomass for biofuels, presents promising opportunities for reducing agricultural sector emissions and sequestering CO_2.

Carbon farming has emerged as a promising strategy for mitigating climate change while improving agricultural sustainability. It encompasses agricultural practices designed to increase carbon sequestration in soils and vegetation and/or reduce GHG emissions from farming activities (FAO, 2017). These practices aim to reduce emissions, enhance soil health, and improve nutrient and water management, ultimately contributing to both climate change mitigation. India's carbon stock has reached 30.43 billion tonnes of CO_2 equivalent as of 2024 (PIB, MoEFCC 2024). Key carbon farming practices include conservation tillage, cover cropping, crop rotation, improved livestock management, biochar application, and agroforestry. Conservation tillage, such as no-till or reduced tillage, minimizes soil disturbance, reduces erosion, and enhances soil organic matter (Lal, 2004). Cover cropping, where non-crop species are planted between main crops, promotes soil health, increases organic matter, and can fix nitrogen, reducing the need for synthetic fertilizers and mitigating nitrous oxide emissions. Crop rotation improves soil fertility, reduces pest pressures, and helps sequester carbon through deep-rooted crops (Rotz *et al.,* 2008). Improved livestock management practices, such as dietary adjustments and better manure management, reduce emissions from livestock (Herrero *et al.,* 2013). Biochar application enhances soil carbon storage by providing a stable form of carbon that persists in the soil for long periods, improving soil fertility and water retention. Agroforestry, which integrates trees into agricultural landscapes, promotes carbon sequestration in both biomass and soil while enhancing biodiversity and ecosystem resilience (Avasthe *et al.,* 2023).

The implementation of carbon farming practices offers several benefits beyond climate change mitigation, including enhanced agricultural productivity. These practices help sequester carbon, reduce GHG emissions, improve soil fertility, and increase water retention, boosting resilience to climate variability. Furthermore, carbon farming can support biodiversity and water quality by minimizing soil erosion and nutrient runoff. However, accurate quantification of carbon storage and emissions reductions requires robust monitoring and verification systems in carbon farming. The permanence of carbon sequestration is another concern, as carbon stored in soils can be lost due to erosion, oxidation, or changes in land use. Successful implementation also requires addressing farmers' concerns, providing adequate technical support, and creating favorable policy frameworks. Moreover, the development of transparent and reliable carbon markets is crucial to incentivize participation and ensure that carbon credits reflect real, verifiable emissions reductions. This study aims to provide a comprehensive overview of the role of carbon farming in addressing climate change. It examines the impacts of climate change on agriculture, agriculture's contribution to GHG emissions, and the potential of carbon farming practices to mitigate these effects. The paper also explores key carbon farming practices, their associated benefits, and the challenges involved in implementing them across various agricultural systems.

Impact of climate change on agriculture and its mitigation strategies

Climate change has significantly impacted various aspects of human life, with agricultural systems being particularly vulnerable to its effects. The role of GHGs in driving global warming is well-established, with scientific evidence attributing increased atmospheric concentrations of CO_2, CH_4, and N_2O to anthropogenic activities, primarily since the Industrial Revolution. The global mean surface air temperature has increased by approximately 0.74°C over the last 100 years. It is projected to rise by 0.3-2.5°C over the next 50 years, with more significant increases anticipated in the coming century (IPCC, 2007). The rate of radiative forcing of these key GHGs has increased significantly over the last 10,000 years, largely due to human activities, with CO_2 concentrations rising by 30%, CH_4 by 145%, and N_2O by 15% (IPCC, 2007).

In India, agriculture accounts for a significant portion of the nation's GHG emissions, contributing 13.72% (PIB, MoEF&CC, 2025). Among the primary sources of these emissions are enteric fermentation in livestock, rice cultivation, manure management, agricultural soils, and the burning of crop residues. While the agriculture sector is a major emitter, it also presents considerable opportunities for mitigating GHGs through practices that reduce emissions and increase carbon sequestration. Enteric fermentation from livestock, particularly ruminants, is the largest source of agricultural GHG emissions in India, accounting for about 66.6% of the sector's total emissions (Nugrahaeningtyas *et al.,* 2024). Ruminants produce methane through microbial fermentation in their digestive systems, particularly in the rumen. Methane has a global warming potential far greater than CO_2, making it a critical target for mitigation. Globally, raising livestock emits almost 120 million tonnes of methane (or 3.3 billion tonnes of CO_2e) per year into the atmosphere (Ferreira and

McCabe, 2024). To mitigate enteric methane emissions innovative strategies, include dietary strategies, such as feeding livestock higher-quality feeds and incorporating feed additives like tannins, fats, or oils. Genetic improvements to livestock can also enhance feed conversion efficiency, reducing methane emissions per unit of livestock production. However, the practical adoption of these strategies faces challenges due to economic constraints, particularly in smallholder farming systems. The decomposition of manure under anaerobic conditions, particularly in improper storage facilities, leads to the release of these gases. Biogas technology involves the anaerobic digestion of manure to produce methane for energy use, and offers a promising solution for reducing GHG emissions. However, biogas technology is not widely adopted, largely due to high initial investment costs, lack of infrastructure, and the need for greater awareness in rural areas.

Rice paddies are another significant source of methane emission, primarily due to the flooded conditions under which rice is traditionally cultivated. Methane is produced in anaerobic conditions created by flooded fields, with rice cultivation contributing to about 4 million tons of methane emissions annually (Gupta *et al.,* 2009). Alternate wetting and drying (AWD) is a promising practice for reducing methane emissions from rice fields by intermittently drying and re-wetting fields, reducing the time spent under flooded conditions (Avasthe *et al.,* 2023). AWD has been shown to reduce methane emissions by up to 30% (Gupta *et al.,* 2009), but its widespread adoption is hindered by regional variability in water availability and traditional farming practices. The practice of burning crop residues is prevalent due to its cost-effectiveness and the lack of viable alternatives for residue management. However, alternatives such as mulching, composting, and using crop residues for bioenergy production can reduce emissions and provide additional benefits, such as enhancing soil fertility.

The use of fossil fuels in agriculture, including for machinery, irrigation, and transportation, contributes to significant CO_2 emissions. One approach to reducing these emissions is through the use of biofuels, which can replace fossil fuels. The conversion of crop residues into biofuels, such as ethanol or biodiesel, offers a promising pathway for de-carbonizing the agriculture sector. However, the removal of crop residues for biofuel production must be carefully managed to avoid negative impacts on soil health.

Moreover, strategies such as improving livestock feed efficiency, adopting better manure management practices, reducing methane emissions from rice cultivation, increasing soil carbon sequestration, and transitioning to cleaner energy sources in agriculture can all contribute to a more sustainable and low-carbon agricultural system. However, widespread adoption of these practices will require addressing economic, infrastructural, and knowledge-related barriers.

Methods of carbon farming

Carbon farming involves a set of agricultural and land management practices that focus on sequestering carbon from the atmosphere and reducing greenhouse gas (GHG) emissions. These practices help enhance soil health, improve agricultural productivity, and promote environmental sustainability. Carbon farming methods can vary depending on local environmental conditions, land use practices, and agricultural systems. Some of the carbon farming tactics are given below.

Forest management

According to the Intergovernmental Panel on Climate Change (IPCC), deforestation accounts for ~ 15-20% of global GHG emissions (IPCC, 2007). Therefore, improving forest management practices is essential for maintaining and enhancing carbon storage in forests. Data suggest that forests take up an average of 3.5 billion metric tons of carbon per year, which is nearly half of the carbon dioxide emissions from burning fossil fuels between 1990 and 2019 (Pan *et al.,* 2024). Improved forest management includes practices such as selective harvesting, thinning, regeneration, and the prevention of illegal logging. These practices aim to maintain healthy and diverse ecosystems that continue to sequester CO_2. Furthermore, reforestation and afforestation efforts can contribute to carbon sequestration by increasing the overall forest cover.

In India, deforestation remains a significant concern, and implementing improved forest management practices offers a sustainable way to mitigate climate change while also supporting biodiversity. The country's total forest and tree cover covers ~ 25.17% of the nation's geographical area. The total carbon stock in India's forests is now estimated at 7,285.5 million tonnes, reflecting an increase of 81.5 million tonnes compared to the previous assessment (PIB, MoEFCC 2024).

Grasslands conservation

Global grasslands account for about 37% of Earth's terrestrial surface (O'Mara, 2012), serving as an important global conservation to safeguard biodiversity. Grasslands store approximately one-third of the global terrestrial carbon stocks, making them one of the largest carbon sinks on land. In India, the conservation of native grasslands is essential for maintaining soil health, supporting biodiversity, and enhancing carbon sequestration. The degradation of grasslands, often due to overgrazing, agricultural expansion, and urbanization, can release stored

Table 1. Enhancing carbon economy in Indian agriculture: mitigation potential, challenges, and strategic approaches

Area of focus	Potential for mitigating GHG emissions	Constraints	Strategic approaches
Enteric fermentation	• Reduction of methane (CH_4) emissions from livestock, which account for 63% of agricultural emissions.	• Difficult to implement in small-scale farming systems. • Requires infrastructure and access to feed technology.	• Promote feed additives, such as tannins or fats, to reduce CH_4 production. • Develop training programs for farmers on efficient feed practices. • Provide financial incentives for adopting methane-reducing technologies.
Manure management	• Reduced methane and nitrous oxide (N_2O) emissions through biogas generation.	• Biogas technology is not widely adopted or available in all regions. • High initial costs and lack of awareness.	• Government subsidies or low-interest loans for biogas installations. • Awareness campaigns to educate farmers on the benefits of biogas. • Strengthen local biogas technology supply chains.
Rice cultivation	• Potential to reduce CH_4 and N_2O emissions from flooded rice fields.	• Diverse soil and climatic conditions make consistent emission reduction difficult. • Adoption of new practices may face resistance.	• Encourage the adoption of water management techniques like alternate wetting and drying (AWD). • Offer financial support or incentives for AWD adoption. • Conduct region-specific research to tailor practices to local conditions.
Soil carbon sequestration	• Significant potential for carbon storage through improved management and restoration of degraded soils.	• High uncertainty in estimates of sequestration capacity.	• Implement conservation tillage and agroforestry systems. • Support research on improved soil management practices. • Promote policies that encourage soil restoration and carbon sequestration.
Field burning of crop residues	• Reducing the burning of crop residues helps lower CH_4 and N_2O emissions.	• Farmers may be reluctant to change practices due to labor and financial constraints. • Lack of alternatives for residue disposal.	• Provide farmers with subsidized or accessible machinery for residue management (e.g., baling, composting). • Educate farmers on the environmental and economic benefits of residue management alternatives. • Implement policy incentives to discourage field burning.
De-carbonization of Fuel and Alternate Energy	• Biofuels from crop residues can help displace fossil fuels, reducing CO_2 emissions.	• Potential adverse effects of crop residue removal on soil health. • Lack of infrastructure for biofuel production.	• Develop infrastructure for processing crop residues into biofuels. • Introduce subsidies or financial incentives for biofuel production. • Promote research on sustainable biofuel feedstocks and techniques that balance energy production with soil health.

Source: NAAS policy paper (2014)

carbon into the atmosphere, exacerbating climate change. Conservation of grasslands involves preventing overgrazing, preventing the conversion of grasslands to agricultural land, and restoring degraded grassland areas.

Renewable energy production

The shift from fossil fuel-based energy sources to renewable energy systems such as wind, solar, and biomass energy is a key method for reducing GHG emissions in agriculture and the wider economy. Fossil fuel-based energy production is one of the largest contributors to CO_2 emissions globally. By displacing carbon-intensive electricity production, renewable energy systems generate carbon offsets that help mitigate climate change.

Fertilizer management

The excessive use of chemical fertilizers in conventional farming practices not only harms soil health but also leads to the release of significant amounts of greenhouse gases (Gouda *et al.,* 2023; Kumar *et al.,* 2024). Up to 60-70% of GHG emissions from fertilizers occur during their field application, while the remaining 30-40% are emitted during production. Therefore, it is crucial to address both aspects to mitigate the impact of fertilizer use on global warming. Globally manure and synthetic fertilizers emit a total of 2.6 gigatons of carbon annually (Gao and Cabrera, 2023). In addition to reducing fertilizer application, farmers can adopt organic farming practices, such as composting and using organic manure, to enhance soil fertility without increasing GHG emissions (Manjappa *et al.,* 2023). Organic farming practices, such as mulching and crop rotation, can help build soil organic matter, reduce the need for chemical fertilizers, and enhance carbon sequestration.

Reduced tillage

Tillage, particularly deep tillage, releases carbon stored in the soil as CO_2 into the atmosphere (Avasthe *et al.,* 2023). Traditional plowing and tillage practices disturb the soil, which can lead to soil degradation, reduced soil fertility, and increased carbon emissions. Reduced tillage or no-till farming involves minimal soil disturbance and helps preserve soil organic carbon. These practices are beneficial for maintaining soil structure, preventing erosion, and enhancing water retention (Verma *et al.,* 2023).

Improved residue management

Burning of crop residues is a common practice. However, this practice releases large amounts of CO_2, CH_4, and N_2O into the atmosphere, contributing significantly to global warming. India generates ~500 million tons (MT) of crop residues annually, a figure significantly higher than many other countries in the region. Of this, around 141 MT of surplus crop residue is produced, with 92 MT being burned (Gatkal *et al.,* 2024). Globally, around 450 million tonnes of crop residues are burned each year, contributing to 1.2 million tonnes of methane emissions (Patel and Panwar, 2023). However, if these residues were incorporated into soil through practices like conservation tillage or used for biochar production, they could play a crucial role in carbon storage. Likewise, residue retention, mproves soil fertility, enhances microbial activity, and contributes to carbon sequestration.

Greening fallow land

As per the Fifteenth Finance Commission report, available underutilized land resources, like cultivable wastelands and fallow lands in India can be deployed to achieve self-sufficiency in wood and greening missions (HLEG, 2020). Bare fallows, where soil is left uncultivated between crop cycles, allow carbon to escape from the soil. Instead of leaving soil bare, farmers can grow nitrogen-fixing cover crops, such as clover or legumes, during fallow periods (Avasthe *et al.,* 2023). These cover crops not only help maintain soil carbon levels but also improve soil fertility by adding organic matter and fixing nitrogen. Growing cover crops during fallow periods prevents soil degradation, enhances biodiversity, and increases soil organic carbon content. Additionally, cover crops provide habitat for beneficial insects and help break pest cycles, reducing the need for chemical pesticides. In semi-arid regions with long dry seasons or intensive mono-cropping systems, planting cover crops can help restore soil health and maintain carbon levels in the soil. There is a huge scope for raising trees and agroforestry on fallow land, cultivable waste, and field boundaries. India also has 12 million hectares of cultivable wastelands that can support meeting domestic demand for wood along with environment, ecology, and sustainability (Chand, 2023; Patel *et al.,* 2024).

Cover crops and companion cropping

Cover crops are vital for improving soil health and increasing carbon sequestration. These crops, which are planted between regular cash crops, help protect the soil from erosion, increase soil organic carbon, and reduce soil disturbance. Cover crops, such as legumes, grasses, and brassicas, are particularly beneficial for improving soil structure, reducing nutrient leaching, and enhancing water retention (Yadav *et al.,* 2024). Companion cropping involves planting two or more crops together to support each other's growth and create a more resilient farming system. This practice helps reduce pest and disease pressure, increases plant diversity, and promotes soil health.

Companion crops can also help reduce soil disturbance, improve nutrient cycling, and enhance carbon storage.

Agroforestry

Agroforestry is the integration of trees with crops or livestock in farming systems. This practice offers several benefits, including above-ground carbon sequestration, improved biodiversity, and increased farm resilience. In India Currently, the total area dedicated to agroforestry is approximately 28.42 million hectares, which accounts for about 8.65% of the country's total geographical area (Arunachalam *et al.,* 2022). Converting underutilized areas, particularly wastelands, can provide numerous benefits associated with agroforestry under diverse agroecosystems. Implementing agroforestry practices to green these wastelands can significantly contribute to climate change mitigation, enhance socio-economic welfare, and help achieve targets set by the Bonn Challenge, the Sustainable Development Goals (SDGs), and the Paris Agreement. Trees sequester carbon through both their biomass and their root systems, which helps mitigate climate change. Furthermore, agroforestry practices provide diverse products, such as timber, fruits, and fuelwood, which can diversify income sources for farmers.

Conservation effective water management practices

Efficient water management is critical for reducing GHG emissions and enhancing carbon sequestration in agricultural systems. Poor water management can lead to soil erosion, nutrient leaching, and reduced carbon storage. By optimizing irrigation schedules and using water-efficient technologies, such as drip or sprinkler irrigation, farmers can reduce the amount of water needed for crops, thus minimizing energy use and reducing CO_2 emissions.

Blue carbon

The term "blue carbon" specifically refers to coastal habitats like mangroves, seagrasses, and tidal marshes, which can sequester and store carbon at significantly higher densities than terrestrial ecosystems, making them highly effective in climate change mitigation over relevant timescales (Lovelock and Duarte, 2019). These blue carbon ecosystems collectively store around 33 billion tonnes of carbon globally, and their large-scale protection and restoration could prevent the release of up to 466 Teragram (Tg) of CO_2 annually (Macreadie *et al.,* 2021).

The potential of carbon farming in India

India has vast potential for carbon farming, primarily through its agricultural land and extensive cropping systems. The country's agricultural sector, with its diverse cropping systems, offers ample opportunities for carbon sequestration and emission reductions. One of the most promising areas for carbon sequestration is soil management. India could sequester up to 52 million tons of carbon annually through improved soil management practices (Lal, 2004). Practices such as conservation tillage, agroforestry, and crop rotation are particularly effective in improving soil organic matter, which is key to increasing soil carbon storage (Lal, 2021).

Agroforestry systems, which integrate trees with crops, are another major contributor to India's carbon sequestration potential. The potential of agroforestry systems to accumulate C is estimated to be 0.29–15.21 t/ha/year (Dhyani *et al.,* 2020). The carbon sequestration potential of AFS can be enhanced by stabilizing soil organic carbon through possible mechanisms including biochemical recalcitrance and physical protection and also reducing C losses. Overall, carbon farming practices not only contribute to reducing emissions but also provide long-term sustainability benefits. These practices can improve soil fertility, enhance water retention, and increase resilience to climate change. However, realizing their full potential requires addressing significant challenges, including the scaling up of these practices.

Despite its potential, the widespread adoption of carbon farming faces several challenges in India. One of the primary barriers is the economic constraints faced by smallholder farmers. Many of the technologies involved in carbon farming, such as biogas digesters, improved feeds for livestock, and agroforestry systems, require substantial initial investments. Smallholder farmers, who constitute the majority of India's agricultural population, often lack the financial resources to adopt these practices, making it difficult to scale up carbon farming across the country. Another significant challenge is the lack of knowledge and awareness among farmers about the benefits of carbon farming practices. Many farmers remain unaware of the climate mitigation potential of practices like conservation tillage, agroforestry, and AWD. Additionally, there is a lack of access to technical training and extension services that could help farmers adopt these practices. The infrastructure necessary for implementing and scaling up carbon farming practices is also inadequate in many parts of India. Policy and regulatory barriers also hinder the adoption of carbon farming practices. While India has established some policies to address climate change and promote sustainable agriculture, there is a need for clearer and more consistent policies related to carbon farming. Financial incentives, such as subsidies for carbon farming practices or access to carbon markets, are often limited or poorly implemented. Additionally, the monitoring, reporting, and verification (MRV) systems required to track emissions reductions and carbon sequestration are still

Table 2. Improved farming practices for enhancing carbon storage

Location	Improved carbon farming practices	Traditional practices	Impact/differencesin carbon storage	References
United States	No-tillage and organic inputs	Tillage with no chemical or organic inputs	Corresponding increases of soil organic carbon (SOC) by 83-104% and 19-32%, respectively	(Wang *et al.*, 2011)
Haryana, India	Maize + cowpea inter-cropping system	Sole maize system	Increased SOC by 29.4-81.65%	(Tripathi *et al.*, 2021)
Mizoram, India	Maize + turmeric inter-cropping system Maize + bean inter-cropping system	Sole maize system	SOC increased by 15.53% in maize + turmeric and 28.64% maize + bean system	(Sahoo *et al.*, 2015)
Sikkim, India	Maize–rajmash–buckwheat system	Maize–black gram–toria system	Less carbon footprint(0.06 kg CO_2-eq per kg production)	(Babu *et al.*, 2023)
Bhopal, India	90% of crop residue retained on the soil surface in the Soybean-wheat system	No residue retention in the Soybean-wheat system.	SOC significantly increased from 0.67 to 1.0% in 5 years	(Yadav *et al.*, 2021)
South-Western Vietnam	Wetland forest (Melaleuca forest) in the open depression of the floodplain	Flooded grassland in the closed depression of the floodplain	Recorded 2.8% higher SOC	(Ly *et al.*, 2022)
Bari, Italy	Organic system	Conventional system	1.18 t/ha/year negative net carbon flux	(Mohamad *et al.*, 2016)
Report from reviews synthesis	Animal manure	Crop residues	Sequestering 20% more soil organic C	(Bolinder *et al.*, 2020)
Baramati, Maharashtra	Residue retention practices	Conventional practices	Higher carbon sequestration (0.68Mg C/ha/yr) and carbon retention efficiency (37%)	(Pradhan *et al.*, 2023)

underdeveloped, limiting the ability of farmers to participate in carbon markets. The issue of permanence in carbon sequestration also presents a challenge. Soil carbon sequestration, for example, is not permanent, as carbon stored in the soil can be lost due to changes in land management practices, erosion, or other factors. Ensuring the long-term effectiveness of carbon farming practices requires addressing these challenges and developing robust mechanisms for monitoring and verifying carbon sequestration over time.

Some Government initiatives/programmes for carbon management

Several initiatives and programs have been introduced aimed at managing and reducing carbon emissions, aligning with its climate change commitments.
Net Zero: The Net Zero initiative plays a crucial role in reducing carbon loss by aiming to balance the amount of CO_2 emitted with an equivalent amount removed from the atmosphere. Introduced in the Paris Agreement (2015), Net Zero sets a long-term goal to halt the increase in atmospheric carbon and stabilize global temperatures. Many countries, including India, have set Net Zero targets. Achieving Net Zero will significantly reduce carbon emissions and prevent further carbon loss to the atmosphere, contributing to climate stability and sustainability.
De-carbonization: De-carbonization directly addresses carbon loss by reducing dependence on fossil fuels and transitioning to renewable energy sources. This process, emphasized by global climate agreements like the Kyoto Protocol (1997) and the Paris Agreement (2015), involves significant reductions in carbon emissions from sectors like energy, industry, and transport. The European Union's Green Deal (2019) set ambitious emission reduction targets. Through de-carbonization, carbon emissions are reduced, minimizing the carbon loss to the atmosphere and contributing to long-term climate goals.
Green Hydrogen: Green hydrogen plays a key role in reducing carbon loss by providing a clean energy alternative to fossil fuels, particularly in sectors like heavy industry and transport (European Commission, 2021). Produced using renewable energy through electrolysis, green hydrogen emits no CO_2, preventing carbon loss from traditional energy sources. The European Union's Hydrogen Strategy (2020) and India's National Green Hydrogen Mission (2021) aim to scale up green hydrogen production, thereby reducing emissions and carbon loss across hard-to-decarbonize sectors and helping achieve long-term climate goals.
Carbon Capture, Utilization, and Storage (CCUS):

CCUS technology directly addresses carbon loss by capturing CO_2 emissions from industrial sources and power plants before they are released into the atmosphere. The first large-scale CCUS project began in 1996 in Norway, and since then, the technology has been recognized as essential for reducing carbon emissions. The IEA's 2020 roadmap set a target to capture 4 billion tonnes of CO_2 annually by 2050. In India, CCUS is seen as a key tool for decarbonizing industries and power generation, helping to reduce carbon loss and store it safely underground or utilize it in products, thereby mitigating climate change.

Carbon Credit Trading Scheme (CCTS): On June 28, 2023, the Government of India launched the Carbon Credit Trading Scheme (CCTS) under the Energy Conservation Act, 2001 (Amendment, 2022), to establish a national carbon market. This initiative is part of India's broader strategy to reduce greenhouse gas emissions and transition to a low-carbon economy. Carbon Capture, Utilization, and Storage (CCUS) plays a pivotal role in decarbonizing the industrial and power sectors, helping India meet its sustainability targets while promoting the production of clean energy and products. This is also aligned with the vision of an Atmanirbhar Bharat, contributing to India's energy independence and sustainable growth.

Amrit Dharohar: Launched by Govt of India on June 5, 2023, the Amrit Dharohar implementation strategy focuses on four key components: Species and Habitat Conservation, Nature Tourism, Wetlands Livelihoods, and Wetlands Carbon. The Ministry of Environment, Forest and Climate Change (MoEF&CC) has issued a Standard Operating Procedure (SOP) for assessing carbon stocks in wetlands.

National Afforestation and Eco-development Board (NAEB): The National Afforestation and Eco-development Board (NAEB) is implementing the Nagar Van Yojana (NVY), which aims to develop 600 urban forests (Nagar Vans) and 400 urban gardens (Nagar Vatikas) across India from 2020-21 to 2026-27. This initiative seeks to enhance green cover outside of forests, improve biodiversity, and provide ecological benefits to urban and peri-urban areas. The program also aims to improve the quality of life for city residents.

India is making strides toward integrating carbon farming into its agricultural policies, particularly through the development of a framework for its voluntary carbon market (VCM). This initiative, though still in its early stages, holds the promise of creating a platform where farmers can engage in carbon trading. To ensure the success of the VCM and its ability to scale up, it is essential to address the socio-economic inclusion issues. Projects that achieve higher levels of inclusion can be incentivized with higher carbon credit prices, thus promoting equity and ensuring that the benefits of carbon farming reach all sections of society. In addition, to enhance the additionally and permanence of carbon farming practices, it is crucial to foster collaborations between project developers and key agricultural research institutions such as the Indian Council of Agricultural Research (ICAR), Krishi Vigyan Kendra (KVKs), state agricultural universities (SAUs), and non-governmental organizations (NGOs).

Carbon credit, trading, and offsets

A carbon credit is a tradable, non-physical asset that represents one tonne of carbon dioxide equivalent (CO_2e) that has been reduced, avoided, or sequestered by a specific project. It is certified and verified according to internationally recognized carbon accounting standards. These credits are granted to verified carbon projects through standards like Verra, Gold Standard, or Plan Vivo. After being issued, carbon credits can be sold in carbon markets, where individuals and organizations looking to reduce their carbon footprint can purchase credits to offset their own emissions. Carbon credits are created through voluntary emission reduction projects or programs. These initiatives are carried out by for-profit or nonprofit organizations whose activities help avoid or remove emissions. Carbon projects can be managed by organizations directly involved in emission reduction efforts, such as a conservancy overseeing land and wildlife preservation or a waste management company handling daily recycling operations. Alternatively, these projects can be managed by third-party entities that specialize in developing carbon projects on behalf of other organizations.

Carbon credit prices in the voluntary market can vary depending on the type of project and tend to fluctuate from year to year.

India has market-based systems such as the Perform, Achieve, and Trade (PAT) scheme and the Renewable Energy Certificate (REC) mechanism. The sectors currently covered by these schemes will continue to be obligated under the Indian Carbon Market (ICM). Additionally, the ICM will allow participation from other sectors not currently part of the PAT or REC schemes, enabling them to trade carbon offsets.

Carbon offsets are tradable certificates that represent actions aimed at reducing carbon dioxide (CO_2) emissions in the atmosphere. Carbon offsets have become a critical business strategy for companies recognizing the growing opportunities in low-carbon markets (Gopinath *et al.,* 2025). By purchasing these certificates, individuals or organizations can support projects that help combat climate change, rather than directly reducing their emissions. Essentially, these certificates "neutralize" the buyer's CO_2 emissions by funding equivalent reductions elsewhere. Carbon offsets help reduce CO_2 in the atmosphere by funding projects that lower emissions or capture and store CO_2, like reforestation, renewable energy, or carbon-storing farming practices. These projects earn carbon offsets, which are sold to companies to balance their emissions by funding CO_2 reduction elsewhere.

While carbon offsets are useful, they come with challenges. Projects must prove they reduce emissions and accurately measure CO_2 savings, which requires strict standards and verification, making the process costly and complex. Despite these challenges, offsets can help companies or countries meet emissions goals more affordably. However, concerns include "over-crediting" (selling offsets that don't reduce emissions as much as claimed) and the risk of companies using offsets to avoid cutting their emissions. When used properly, offsets can be an effective tool in combating climate change.

Constraints and challenges

Despite the positive developments, carbon farming faces challenges that may limit its widespread adoption. The transition to carbon farming often requires upfront investment in new practices, which can be economically challenging for farmers, especially in developing countries. Climate change itself poses a paradoxical threat to the success of carbon farming practices. The changing patterns of rainfall, temperature extremes, and the increasing frequency of extreme weather events, such as floods and droughts, can undermine the effectiveness of certain practices. For example, conservation tillage may be less effective in regions that experience prolonged droughts, while agroforestry systems could be vulnerable to higher temperatures and shifting growing seasons. As a result, climate change may create uncertainties around the long-term viability of carbon farming techniques. Access to financial resources, technical knowledge, and training is another key constraint. In the case of carbon markets, the process of earning and trading carbon credits requires a well-established infrastructure, including certification processes, monitoring systems, and a clear regulatory framework. Without access to these resources, farmers may not see the financial returns necessary to justify the switch to carbon farming. Additionally, while carbon credits provide a potential source of income, the volatility and complexity of carbon markets can discourage participation, particularly among small-scale farmers who lack the technical expertise to navigate the carbon trading system. Furthermore, as the demand for carbon credits rises globally, there may be competition for credits between different countries, industries, and farming sectors. This could result in price volatility, limiting the attractiveness of carbon markets for smallholder farmers.

Carbon farming offers immense potential in mitigating climate change by sequestering CO_2 in agricultural landscapes through various sustainable agricultural practices. Significant amounts of atmospheric carbon can be captured and stored in soil and biomass by implementing strategies such as agroforestry, conservation tillage, biochar application, and improved crop and livestock management. These practices not only contribute to reducing greenhouse gas emissions but also provide a range of co-benefits, including enhanced soil fertility, improved water retention, increased biodiversity, and stronger agricultural resilience to climate extremes.

Government policies play a crucial role in driving the adoption of carbon farming in India. Initiatives such as climate action plans, the promotion of green hydrogen development, and efforts to support carbon capture, utilization, and storage (CCUS) contribute to a broader strategy for sustainable climate management. Carbon trading systems, along with private soil carbon certificates, provide essential financial incentives to farmers, enabling them to monetize the environmental benefits they generate through carbon sequestration. The growth of carbon markets, both domestic and international, offers a pathway to integrate agricultural emissions reductions into the global carbon economy, creating opportunities for farmers to be rewarded for their efforts in climate mitigation.

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