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REVIEW ARTICLE

Carbon farming: A pathway to mitigate climate change for sustainable agriculture

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Abstract

In the twenty-first century, climate change results in a combination of natural and human impacts, including extreme weather and variability. Carbon farming has the opportunity to significantly reduce global warming while increasing resilience. Carbon farming is a holistic agricultural practice that seeks to minimize climate change and enhance ecologically sound sustainable farming. Enhancing soil and vegetation's potential to capture atmospheric carbon dioxide (CO_2) may assist in mitigating greenhouse gas emissions while also enhancing soil health and agricultural productivity. This review explores the key carbon farming practices such as conservation agriculture (CA), agroforestry, cover cropping, intercropping, tillage practices and mulching and their role in promoting soil organic carbon and reducing greenhouse gas (GHG) emissions. Global programs such as the Agricultural Carbon Project in Australia and Kenya, the Chicago Climate Exchange and the 4 of 1000 Initiative, indicate that carbon farming might boost food security while simultaneously addressing climate change. High-impact regions can enjoy economic gains amounting to as much as $63 billion from things like crop rotation and organic farming under the umbrella of emissions trading initiatives that encourage environmentally sound agricultural techniques. However, drawbacks include a lack of financial assistance, ineffective policies and restricted supply of water. Carbon farming may be efficiently promoted with strong government assistance, financial incentives and improved stakeholder awareness. Through increased adoption of carbon farming practices, agriculture becomes more resilient, sustainable and aligned with sustainable development goals (SDG).

Keywords: carbon trading; conservation agriculture; greenhouse gas; soil organic carbon

Introduction

Climate change has a considerable impact on agriculture, posing problems for food supply, accessibility and the livelihoods of small-scale farmers (1). Climate change exacerbates agriculture's environmental effect by reducing productivity, causing soil erosion and magnifying GHG emissions, emphasising the critical need for environmentally friendly, climate-resilient agricultural techniques (2). Elevated CO_2 levels degrade soil and impair crop nutritional value, particularly for cereals. With GHG emissions such as CO_2, methane and nitrous oxide contributing to unprecedented climate change, emission reduction techniques are crucial. For example, the Europian Union (EU) aims to reduce GHG emissions by 55 % by 2030, with a more ambitious 90 % reduction by 2040 (3).

Conventional farming practices have reduced soil organic matter and led to 24 % of world GHG emissions, largely from cattle, resulting in 7.1 gigatons of CO_2 equivalent per year or 14.5 % of total human-caused GHG emissions. Carbon farming appears to be a promising solution, as it incorporates measures that trap atmospheric carbon into soil, crops and vegetation while offering revenue through carbon credits (4). Regenerative practices like conservation tillage, crop stubble management and cover cropping improve soil health, biodiversity and ecological resilience (5). To address environmental, economic and social challenges, sustainable agriculture must prioritize environmental stewardship alongside profitability and social responsibility. This review explores carbon farming's potential, benefits and limitations, emphasizing its role in promoting sustainability, increasing farmer living standards and guiding future research and policy actions.

Climate change mitigation through carbon farming

Carbon footprinting

To mitigate GHG emissions and enhance GHG sinks within a system, the carbon footprint (CF) framework identifies the sources, quantities and sinks of GHGs generated through both on-farm and off-farm activities (6). CF analysis encompasses all inputs and processes within the boundaries of a specified system. The system limit, which is developed as a conceptual barrier based on the behaviours and materials involved, defines the assessment's scope. While CF research provides important insights for making educated decisions, current approaches for measuring CF in agricultural systems are not standardized (7). Inconsistencies can develop in areas such as functional unit selection, system boundary definition and emission factor specificity. Estimating soil GHG emissions from various farming practices is challenging for a variety of reasons, including soil carbon (C) variability and inconsistencies between global and field-scale estimates (8). Meanwhile, the complex dynamics and interactions between labile and recalcitrant carbon pools highlight the importance of integrated approaches to develop standardized procedures and models based on site-specific data. According to the study, small-scale vegetable growing accounts for 13 % of net CF emissions from soil, emphasising the importance of quantifying soil carbon losses and gains (6). As a result, full CF assessments must account for CO_2 emissions and sequestration, as well as the net GHG emissions from specific farms, farm products or field tasks. This is crucial to determining the efficacy of agricultural practices for supporting GHG reduction practices.

Carbon sequestration

Carbon sequestration refers to converting atmospheric CO_2 into long-term soil storage by increasing organic and inorganic carbon stocks through sustainable land use and management methods. Mulch farming, conservation tillage, agroforestry, diversified cropping systems (9), cover crops and integrated nutrient management (manure, compost and enhanced grazing) all help to assist this process. Agricultural methods that promote biomass assimilation, low soil disturbance, improved soil structure and biodiversity are essential for soil organic carbon (SOC) buildup. SOC, which is intimately associated with soil organic matter, has a major impact on soil structure, health, nutrient content and water retention (10).

Research shows that organic farming has the potential to increase SOC. A study found that SOC stocks were 3.50 ± 1.08 Mg C ha^{-1} higher in organic systems over 14 years (11), while another reported a 2.2 % annual SOC increase in organic systems compared to a negligible change in conventional methods (12). Organic farming systems have an annual carbon sequestration advantage of 1.13 tons of C ha^{-1} yr^{-1} compared to conventional practices (13). Organic farming shows significant promise for increasing soil carbon stocks, with estimates of sequestration potential reaching up to 500 kg C ha^{-1} yr^{-1} in Europe (14). For example, the carbon content for each tree species is estimated to be about 50 % of the tree's total biomass (Eqn. 1). To determine the amount of CO_2 stored in trees, the carbon content is multiplied by the CO_2-to-carbon ratio, which is 44/12 or 3.67 (Eqn. 2)(15). An overview of the carbon cycle and its key transformation processes is shown in Fig. 1.

Carbon storage (kg) = total biomass (kg) × 50% or total biomass/2 (1)

CO_2 sequestered (kg) = carbon storage (kg) × 3.67 (2)

Key practices in carbon farming

Carbon farming combines sustainable agricultural practices to increase carbon absorption while lowering GHG emissions. Agroforestry, which combines trees and crops to increase biodiversity and carbon storage and conservation agriculture, which reduces soil disturbance while preserving organic carbon, are two important methods. Cover cropping and intercropping promote soil health and reduce erosion, while biochar enriches soil carbon. Reduced tillage, nitrogen management and rotational grazing all help to boost SOC, hence improving climate resilience and long-term productivity. A visual representation of carbon farming strategies for climate-smart agriculture is given in Fig. 2.

Organic farming

Organic farming has significant potential to address climate change and promote sustainability by sequestering carbon and reducing GHG emissions. Studies show that organic systems have higher carbon sequestration capacity than conventional farming, with practices like organic fertilization, crop residue incorporation and cover crop cultivation boosting soil organic carbon levels (16). However, they may result in increased N_2O emissions, although deep-rooted crops can reduce NO_3 leaching (17). Soil management practices in organic farming, such as organic matter recycling and legume planting, increase soil carbon levels while lowering GHG emissions by reducing dependence on industrial fertilizers and agrochemicals. Organic farming might cut world GHG emissions by 20 % by eliminating industrial nitrogen fertilizers (18), as well as offset 40 %-72 % of yearly agricultural GHG emissions (19).

In India, organic farming is gaining attraction through programs like the Paramparagat Krishi Vikas Yojana (PKVY) and Mission Organic Value Chain Development, which have certified millions of hectares. With a target of 26 million hectares by 2030, India is supporting resource conservation technologies, including solar energy and biogas, to advance sustainable agriculture. A successful transition to organic farming demands an integrated approach involving farmer producer organizations (FPOs) and focuses on regions with low chemical inputs in order to expand techniques. Organic farming has the ability to significantly reduce GHGs and increase SOC (11).

Cover crops

Cover crops such as cowpea, lentil, buckwheat and rye are critical for carbon farming, providing significant benefits for soil carbon sequestration, ecosystem services and GHG mitigation. A study shows that cover crops can significantly reduce soil carbon loss, decreasing it from 498 kg C ha^{-1} yr^{-1} to 57 kg C ha^{-1} yr^{-1} and reducing GHG emissions by 41 % (6). They improve SOC sequestration and soil health, enhance nutrient cycling and increase carbon storage through labile carbon and nitrogen inputs (20). Organic farming systems incorporating cover crops have a lower CF and result in reduced GHG emissions (21). Cover crops, combined with crop rotations, can also boost yields and SOC levels. Global adoption of cover crops is rising rapidly, with 8.9 million hectares currently in use, sequestering over 66 million tons of CO_2 annually. In the EU, cover crops on cropland soils, which lose 7.4 million tons of carbon yearly, offer a mitigation strategy, with high sequestration rates in Olive orchards and Vineyards. A study indicated that without cover crops, 498 kg C were lost from the soil's top 30 cm every year, compared to 57 kg with cover crops, resulting in 1826 kg CO_2 eq ha^{-1} yr^{-1} and 209 kg CO_2 eq ha^{-1} yr^{-1}, respectively (6). In addition, incorporating cover crops resulted in a 41 % reduction in predicted soil greenhouse gas emissions. The trial conducted at Fort Valley State University observed that SOC at 0-10 cm fluctuated with plant carbon input and was greater from cover crops (hairy vetch, rye or a mixture of hairy vetch and rye) over no cover crops (weeds) in cotton (*Gossipium hirsutum* L.) and sorghum (*Sorghum bicolor* L.). Cover crops raised SOC to 120-130 kg N ha^{-1} yr^{-1} compared to 0 kg N ha^{-1} yr^{-1} without cover crops at 0-30 cm depth (22).

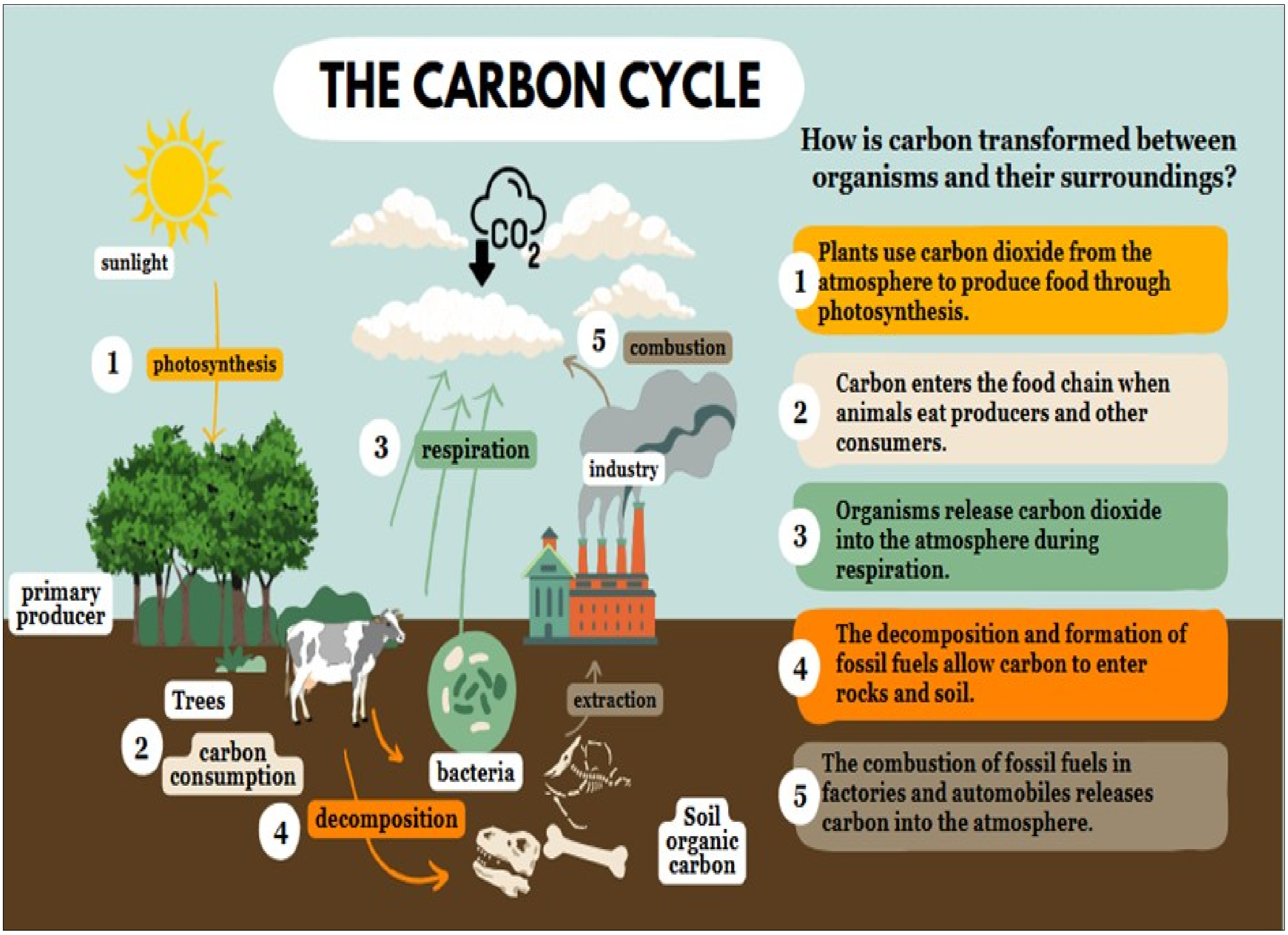

Fig. 1. Visual representation of the carbon cycle and carbon transformation processes.

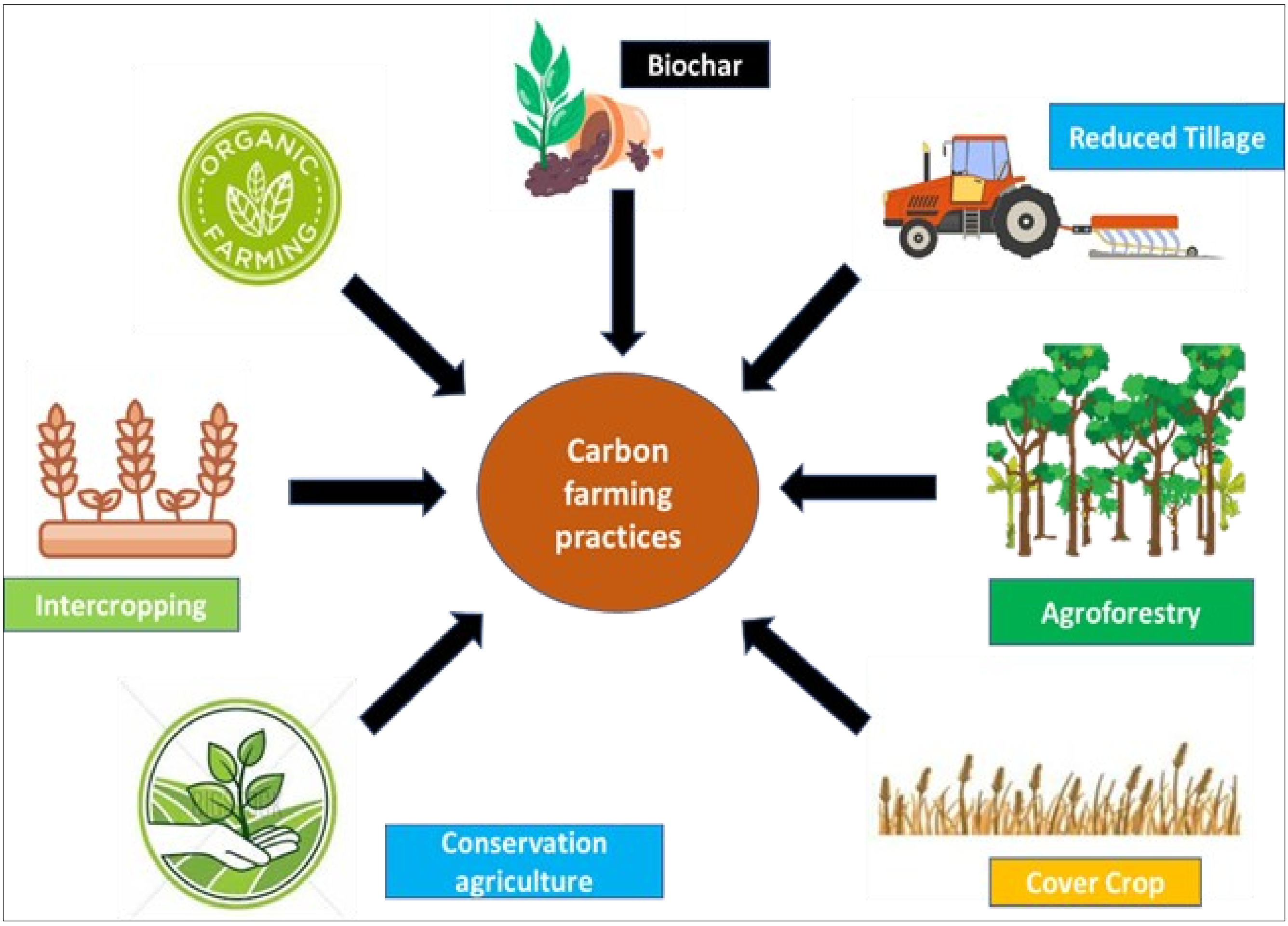

Fig. 2. Key carbon farming practices for sustainable agriculture.

Policymakers are increasingly recognizing the role of cover crops in climate change mitigation. The Biden Administration has proposed a substantial $28 billion budget for land conservation efforts, including a dedicated allocation of $5 billion to support farmers and landowners who choose to adopt cover cropping practices (23). By 2030, cover crops could sequester 132 to 165 million tons of CO_2 annually on 16 to 20 million hectares (24).

Intercrop

Legumes and intercropping systems are crucial for sustainable agriculture and climate change mitigation. Legumes such as peas, beans and lentils, fix atmospheric nitrogen, enriching soil fertility and reducing the need for synthetic fertilizers (25). This process enhances soil health, reduces farming costs and mitigates environmental risks. Intercropping, particularly legume-based systems, improves soil structure, stability and microbial diversity, boosting fertility and resilience (26). Furthermore, intercropping improves carbon sequestration, lowers nitrous oxide emissions and boosts soil carbon stocks (27).

Relay cropping, a type of intercropping, increases resource efficiency, enhances soil fertility and promotes continual vegetative cover (28). These systems are ideal for rainfed and irrigated ecosystems in India, boosting biodiversity, crop yields and pest & disease resistance (29). They are consistent with regenerative agriculture principles, promoting soil health, fertility and organic carbon sequestration while minimizing erosion (30). Intercropping enhances carbon sustainability and is a more efficient alternative to monocropping. List of some maize-based intercropping systems across India is provided in Table 1.

Biochar

Biochar has received attention for its potential for carbon sequestration and as a sustainable agricultural amendment. Approximately 212.04 ± 44.27 metric tons biochar may be generated from 512.82 metric tons gross agricultural residues in India. Cereal crop residues (rice and wheat) include around 63 % biochar potential, while cash crop residues (cotton and sugarcane) account for roughly 17 % of total biochar potential in India. In-situ burnt agricultural residues (124.12 metric tons) have the potential to provide 51.07 ± 10.34 metric tons of biochar (34). Residues from agriculture, forestry, municipal solid waste, food and animal manures and other biomass waste products can be used to make biochar (35). Many agricultural residues have been used to produce biochar, including rice straw (36), wheat straw (37), waste wood (38), sugar beet tailings (39), maize cob (40) and so on. Pyrolysis, hydrothermal carbonization, gasification, flash carbonization and torrefaction are some of the most frequent thermochemical processes used to make biochar (41). Biochar, which is made by pyrolysis or gasification of organic material, improves soil fertility, water retention and SOC sequestration, making it an environmentally favourable option (42). It boosts crop yields by boosting cation exchange capacity, nitrogen retention, pH levels and plant-accessible water, while also promoting beneficial soil microbes. Combining biochar with organic fertilizers increases nutrient availability while decreasing nutrient leaching (43).

Biochar retains about 50 % of the original biomass carbon, compared to lower retention rates in conventional methods like burning (3 %) and microbial degradation (10 %-20 %) (44). It helps to reduce GHG emissions, particularly nitrous oxide and improves soil aggregation (45). However, difficulties such as variability in biochar quality and insufficient policy support impede uptake, particularly in Europe (46). Research should concentrate on optimizing biochar production and examining long-term effects on soil and carbon sequestration (47). Integrating biochar into carbon credit programs may incentivise its use. Biochar made from crop leftovers is an alternative to open burning that retains more carbon and reduces GHG emissions. It also improves soil health and fertility, hence promoting sustainable agriculture in countries such as India. Biochar has the ability to immobilize pollutants and manage waste, benefiting smallholder farmers and promoting the Sustainable Development Goals (SDGs).

Mulching

Bare soil is susceptible to erosion, which depletes topsoil and lowers SOC levels. Mulching with cover crops, crop leftovers and compost reduces erosion and increases SOC sequestration. Mulching enhances soil structure, microbial activity, nitrogen cycling and water retention while also regulating soil temperature (48). It also serves as a carbon sink, contributing to both the carbon and nitrogen cycles. Mulch treatment has been demonstrated to improve soil organic matter (SOM) and carbon sequestration rates by 8-16 Mg ha^{-1} yr^{-1} (49). In certain situations, such as rice residue mulching, it improves crop yield by lowering weed pressure, increasing soil aeration and optimizing water and nitrogen utilization (50). Mulching also captures CO_2 in the topsoil. Agricultural waste has tremendous potential as a biomass energy source in India, but current use is restricted. Punjab, for example, has biomass power facilities but only uses roughly 10 % of its rice crop residue (51). Wheat straw mulching has been examined for its effects on soil water conservation and physical qualities. The study's findings showed that using wheat straw as mulch improved soil's physical and chemical qualities. Wheat straw mulch decomposition increased soil carbon content to a maximum of 10 Mg ha^{-1} yr^{-1} (52).

Tillage practices

Soil disturbance, particularly from tillage, alters soil aggregates and organic matter, increasing erosion and GHG emissions. No-till methods can reduce these effects by promoting soil aggregate formation, improving soil structure and increasing SOC sequestration (53). While no-till farming does not account for all SOC sequestration, it is essential in carbon farming when paired with other methods such as conservation tillage and cover crops (54). These strategies protect SOC, lower CO_2 emissions and improve soil health and sustainability.

Table 1. Effect of maize- legume intercropping systems on soil organic carbon (SOC) content across India

Region	Intercropping system	Soil organic carbon %	Reference
Karnal, Haryana (NW Indo-Gangetic)	Maize + legumes (cowpea, mungbean, blackgram, clusterbean) - Wheat	Legumes increased SOC by 27.61–79.13% compared to sole maize-wheat.	(31)
Eastern Himalayan (rainfed)	Maize + cowpea intercrop - winter crops (rape, barley, pea)	At 0-15 cm SOC was 9.2-16.8% higher in maize + legume -winter crop systems compared to maize -fallow.	(32)
Karnataka (Southern India)	Maize + pulses (field bean var. local, red gram, etc.)	Maize + field-bean var. local crop reached 0.573% SOC compared to sole maize.	(33)

No-till farming reduces GHG emissions by almost one-third while increasing soil carbon storage by limiting oxygen exposure and avoiding microbial breakdown (55). Long-term no-till methods increase carbon accumulation over time. In India, zero tillage has reduced costs, raised earnings and decreased emissions by 1.5 Mg ha^{-1} every season (50). Conventional tillage systems emit more carbon than no-till, while no-till reduces GHG emissions by 30-35 kg C ha^{-1} each season (56). Long-term no-till systems also lower emissions of powerful GHG such as methane and nitrous oxide (57). CA approaches are more widely accepted by farmers in rice-wheat cropping systems that cover more than 10 million hectares in the Indo-Gangetic Plains (IGP). In these systems, any delay in seeding results in a yield loss of 1 %-1.5 % per day after wheat's optimal sowing date. The widespread use of CA approaches in IGP is primarily to combat delayed sowing due to field preparation and weed management, timely planting and the escape from terminal heat in the grain-filling stage. Constraints in CA adoption in South Asia include small land holdings (<1 ha), limited technology access for farmers, lack of appropriate farm implements and a strong traditional mindset (58).

Agroforestry

Agroforestry, which combines perennial trees with crops or livestock, is an ancient method that improves agricultural self-sufficiency, minimizes fossil resource consumption and delivers different goods (59). It is especially useful for smallholder farmers, like those in Latvia, where 26 % of agricultural land is owned by smallholders (60). Agroforestry diversifies output while providing environmental, economic and social benefits such as reduced soil erosion, better soil condition and higher weather proofing (61). It improves biodiversity by sequestering carbon in trees and soil, increasing agricultural production and supplying supplementary products such as fruits and feed. Agroforestry covers 15.4 million hectares in the EU, contributing to carbon sequestration, soil quality and biodiversity (62). However, economic challenges and lack of policy support are slowing its growth across Europe (63). Agroforestry covers 80.9 million hectares in India, with government support for afforestation, land restoration and tree planting outside of forests (64). Agroforestry also adds to biofuels and bioenergy production, particularly in degraded lands and helps to achieve sustainability goals such as land degradation neutrality and the Bonn Challenge for afforestation (65). Carbon sequestration under different agroforestry systems across the world is presented in Table 2. Different agroforestry systems across 15 agroclimatic zones of India are given in Table 3.

Conservation agriculture

CA is an important carbon farming option, which emphasizes on soil health, carbon sequestration and sustainable crop management practices. It emphasizes no-till, reduced tillage, cover cropping and good crop residue management as solutions to India's primary concerns. With an annual agricultural residue production of 683 million metric tons, roughly 178 million metric tons are surplus, whereas 87 million metric tons are burned, generating hazardous pollutants such as PM2.5 and CO_2, primarily from rice and wheat residues (81). Diversifying cropping systems away from typical rice-wheat monoculture helps to alleviate residue-related concerns. CA techniques, including no-till, minimal tillage and crop rotation, boost soil health and carbon sequestration (82).

Table 2. Carbon sequestration under different agroforestry systems across world (66)

Region	Agroforestry Systems	Carbon Sequestration Rate (Mg ha^{-1} yr^{-1})	Soil Depth (cm)	References
Costa Rica	Alley cropping	4.13	60	(67)
Canada	Alley cropping	0.69	60	(67)
Canada	Shelterbelts (six different species)	0.7	50	(68)
India	Agrisilviculture (Poplar based)	1.95	30	(69)
India	Agrisilviculture (Poplar based)	2.63	30	(69)
India	Agrisilviculture (Poplar based)	1.62	30	(70)

Table 3. Carbon sequestration potential of different agroforestry systems across 15 agro-climatic zones in India (71)

Agro-climatic Zones	Agroforestry System	Carbon Sequestration Potential (Mg C ha^{-1} yr^{-1})	References
Western Himalayan Region	Agri-horticulture (*Prunus armeniaca*, *Citrus sinensis*) (*Prunus persica*, *Citrus*)	1.80 2.0	(72)
Eastern Himalayan Region	Silvi-pastoral (*Morus alba* + Setaria grass)	1.55	(72)
Lower Gangetic Plains Region	Agri-silviculture (Eucalyptus tereticornis + rice-wheat)	10.7	(73)
Middle Gangetic Plains Region	Agri-silviculture *Tectona grandis* + sorghum/groundnut	2.32	(72)
Upper Gangetic Plains Region	Agri-silviculture (*Dalbergia sissoo* + mustard)	2.83	(74)
Trans Gangetic Plains Region	Agri-silviculture (*Populus deltoides*, + wheat/potato/turmeric)	9.12	(75)
Eastern Plateau & Hills Region	Agri-silviculture (*Albizia procera* + wheat)	5.70	(74)
Central Plateau & Hills Region	Agri-silviculture (Acacia + greengram-mustard)	3.70	(76)
Western Plateau & Hills Region	Agri-silviculture (*Ailanthus excelsa* + cowpea-mustard)	9.64	(72)
Southern Plateau & Hills Region	Silvipasture system (*Leucaena leucocephala* + *Gliricidia sepium, Stylosanthes hamata*)	23.2	(77)
East Coast Plains & Hills Region	Horti-silviculture *Acacia mangium* + pineapple	5.51	(77)
West Coast Plains & Hills Region	Agri-silvi-horticulture (*Artocarpus heterophyllus*, *Acacia auriculiformis* + black pepper)	9.90 11.3	(78)
Gujarat Plains & Hills Region	Silvo-aromatic (*Melia dubia* + lemon grass)	20–25	(79)
Western Dry Region	Silvipasture system (*Ailanthus* + *Cenchrus ciliaris/Panicum antidotale*)	9.64	(72)
The Island Regions	Horti-pasture (*Cocos nucifera* + *Calliandra calothyrsus)*)	3.50	(80)

CA is specifically beneficial since it sustains and enriches soils during fallow seasons, promotes biodiversity and raises SOC levels. Agricultural soils often contain lower SOC than natural vegetation, with crop cultivation resulting in 30 %-40 % SOC losses (83). SOC sequestration in conventional tillage and no-till systems is dependent on plant carbon inputs and mineralization rates, which are affected by crop management methods. While challenges persist in implementing CA holistically in India's rainfed dryland ecosystems, a tailored approach based on soil type, water availability, farm size and soil depth is essential (84).

Carbon sequestration by soils

Soil management strategies are critical for carbon sequestration, climate change mitigation and soil health enhancement. Studies discovered that site circumstances have a greater influence on carbon sequestration capability than management alone, as does the impact of land use changes on SOC. Conservation farming and crop rotation improve SOC levels and soil quality (85). Paddy soils, for example, store 39 %-127 % more carbon than upland soils, particularly in warmer climates (86). Direct Air Capture (DAC), Carbon Dioxide Removal (CDR) and Carbon Capture and Storage (CCS) are critical methods for controlling global warming (87). Cover cropping, agroforestry and residue management are examples of agricultural practices that replenish lost carbon, improve soil fertility and reduce nitrogen emissions (88). Biochar and peatland restoration both contribute to carbon sequestration, with bioenergy with carbon capture and storage (BECCS) having the potential for net negative emissions if CO_2 is properly stored (89). Additional sustainable techniques for increasing SOC and mitigating climate change are presented in Table 4.

Crop management practices in India

India's 170 million hectares of agricultural land contribute significantly to carbon storage (97). The Energy Conservation Bill (2022) expands the domestic carbon market. Shifting to location-specific seeds, organic manure and leguminous plants cut water use by 40 % and methane emissions by 22 kg per acre. Meghalaya is developing a "carbon farming" framework and Sikkim became the first organic state in 2016 (98). Alternate Wetting and Drying (AWD) is a water-saving strategy for irrigated rice cultivation developed by the International Rice Research Institute (IRRI) Philippines. Water saving using the AWD approach in rice cultivation may help to minimize CH_4 emissions (99). System of Rice Intensification reduces methane emissions four times more than previous approaches (100). Startups repurposing paddy stubble provide environmentally friendly options, while Climate Sense partners with farmers in Maharashtra to provide agro-forestry credits (101). Government programs such as the National Mission for Sustainable Agriculture (NMSA) and PKVY encourage regenerative practices, increasing India's self-reliance (102).

Improving carbon farming practices

Circular carbon economy

Rising consumption and economic activity raise demand for raw materials while also increasing GHG emissions, posing an environmental danger. To fulfil the Paris Agreement's 1.5 °C target, a paradigm shift is required, as climate change might cost the global economy $54 trillion by 2100 (103). Between 1985 and 2015, India's GDP grew at a 6 % yearly rate, resulting in increased resource consumption (104). The circular carbon economy (CCE) encourages emissions reduction, material reuse and renewable energy, resulting in a closed-loop system of "reduce, reuse, recycle" (105). Circular farming optimizes waste, lowers expenses and increases efficiency. Biomass carbon removal technologies, like bioenergy with carbon capture and storage (BECCS) (0.5-5 Gt CO_2), afforestation and reforestation (0.5-3.6 GtCO_2), direct air carbon capture and storage (DACCS) (0.5-5 Gt CO_2), enhanced weathering (2 to 4 Gt CO_2), biochar (0.5 to 2 Gt CO_2) and soil carbon sequestration (<5 Gt CO_2) (106). These technical approaches result in a total annual CO_2 removal of 9-24.6 Gt CO_2, which aligns with the IPCC's targets, with projected costs ranging from $5 to $300 per t CO_2. Regenerative agriculture strategies can reduce GHG emissions, trap carbon in soils & plant biomass and reduce soil damage (107). Circular agriculture integrates mixed systems to reduce CO_2 and promote sustainability. The European Commission estimates circular economy principles could boost GDP by 0.1 % and create 100000 jobs by 2030. Globally, the circular economy could save over $1 trillion annually (108), with India safeguarding $600 billion of GDP. Carbon-negative technologies are essential to meet the IPCC's 1.5 °C target (109).

Monetising carbon credits

Carbon credits, part of the Paris Agreement's cap-and-trade system, allow companies to offset CO_2 emissions by supporting entities like farmers who sequester carbon (110). These credits, based on CO_2-equivalent units, originated from the Kyoto Protocol. McKinsey forecasts a 15-fold increase in carbon credit demand by 2030, benefiting farmers with cash incentives (111). Farmers earn ₹780 per credit, with companies paying greater rates. Carbon farming improves soil qualities and farmers earn 1-4 credits per acre. Technological developments increase carbon sequestration detection and in the EU, soil carbon sequestration certification programs are evolving. Farmers can sell these certificates to offset emissions, helping to fund initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) and the Clean Development Mechanism (CDM) (112).

Rewarding with carbon credits

Integrating technology and private sector participation enables small-scale farmers to get access to carbon credit systems and sequestration potential (113). The '4 per 1000' effort, established

Table 4. Supplementary practices for carbon sequestration and sustainable land management

Other practices	Description	References
Perennial Plants	Perennial crops sequester carbon, improve soil structure and enhance nitrogen dynamics.	(90)
Crop Diversity and Rotation	Crop rotation and diversification improve SOC, biodiversity and yield stability.	(91)
Grazing Management	Rotational grazing boosts SOC, soil structure and biodiversity, promoting long-term carbon sequestration.	(92)
Recycling Crop Residues	Crop residues boost soil fertility by aiding nutrient cycling and supporting microbes.	(93)
Livestock Management	Efficient livestock management cuts methane emissions and boosts productivity sustainably.	(94)
Nutrient Management	Improving nutrient use efficiency reduces fertilizer use, emissions and nutrient runoff.	(95)
Afforestation and Forest Ecosystem Restoration	Afforestation and reforestation sequester carbon, reducing emissions by up to 7 Pg CO_2e annually and enhance biodiversity.	(96)

at the 2015 Paris climate conference, sought to increase soil carbon by 0.4 % per year to balance additional CO_2 emissions (114). In 2021, the Indian Agricultural Research Institute and Nurture Farm reduced CO_2 emissions by one million tonnes through bio-enzyme "PUSA" to decompose rice chaff for improving soil quality and reducing fertilizer reliance (115). Agri-residue biorefining creates valuable products and income opportunities. Companies like McDonald's, Target and Cargill support regenerative practices, while platforms like Crop In offer mobile-based farming advice (116). Supporting sustainable farming could reduce EU GHG emissions by 6 % annually and increase farmers' incomes by €9.3 billion by 2030.

Startups

Startup incubators are crucial in raising awareness of carbon farming and assessing carbon savings through methods like life cycle analysis (LCA), which ensures transparency and prevents greenwashing. These incubators help connect carbon farming outcomes to the carbon credit market and provide necessary patient capital. Startups such as Dehaat and Bharat Rohan work with farmers to promote sustainable practices, while Trace X collaborates with Olam on a blockchain-driven traceability solution for Basmati rice, qualifying it for carbon credits (117). Startups like Nurture Farms, Varaha and Climes offer consultancy, assisting with carbon projects, sustainable financing and navigating carbon markets (118). Additionally, companies like Carbon Craft, Zerund, Krimanshi and Hydro Greens are contributing to carbon reduction in construction and the dairy sector. Nori and Indigo are major agricultural soil carbon offset producers in the U.S. voluntary market, with Indigo launching its program in 2019 and Nori in 2017 (119).

Measuring soil carbon sequestration

Soil carbon encompasses organic (SOC) and inorganic carbon (SIC). SOC is present in fresh plant matter (readily available) and humus or charcoal (inert SOC). SOC sequestration lasts decades, while SIC can last over 70000 years. Methods for sequestration include planting perennial crops, retaining plant residues, minimizing tillage and region-specific practices. There are different methods for measuring SOC (Table 5).

Global initiatives

Several countries and regions have developed carbon farming schemes to incentivize sustainable agricultural practices that contribute to carbon sequestration. In the EU, the Common Agricultural Policy (CAP) integrates climate action, encouraging farmers to adopt practices such as cover cropping and reduced tillage, while funding research and development in carbon farming. The Carbon Farming Initiative, launched as part of the European Green Deal, focuses on creating a standard for carbon farming and establishing a certification process for carbon removals. In the United States, the USDA offers programs like the Conservation Stewardship Program (CSP) and the Environmental Quality Incentives Program (EQIP), which provide financial and technical assistance for adopting carbon farming practices. Additionally, farmers can participate in carbon markets to earn credits for their carbon sequestration efforts, selling them to companies seeking to offset emissions. Australia's Emissions Reduction Fund (ERF) provides incentives for farmers and land managers to adopt practices that reduce GHG emissions and enhance carbon storage, while New Zealand's Permanent Forest Sink Initiative encourages landowners to establish permanent forests for carbon sequestration. In Canada, Alberta's Carbon Offset System allows farmers to generate credits by adopting practices that improve soil carbon content, such as changing tillage methods and managing nitrogen more effectively. China's Grain for Green Program promotes reforestation and grassland restoration, indirectly contributing to carbon sequestration. On a global scale, initiatives like the '4 per 1000' launched during the COP21 climate talks in Paris, emphasize the role of soil carbon sequestration in mitigating GHG emissions by increasing soil organic matter by 0.4 % annually. Kenya's Agricultural Carbon Project, supported by the World Bank, exemplifies how carbon farming can address climate change and food security challenges in developing countries. Voluntary carbon markets in the U.S., Australia, New Zealand and Canada incentivize carbon farming by enabling farmers to earn income through carbon credits. India has also begun laying the foundation for a carbon market with an amendment to the Energy Conservation Act 2001 in 2022, furthering its commitment to carbon sequestration.

Policy actions in carbon farming in India

The Government of India has implemented various initiatives to promote sustainable agriculture and support carbon farming. The National Innovations in Climate Resilient Agriculture (NICRA), a network project by the Indian Council of Agricultural Research (ICAR), aims to enhance the resilience of Indian agriculture by addressing the impacts of climate change on crops, livestock and fisheries. The National Mission for Sustainable Agriculture (NMSA) includes programs such as Soil Health Cards, PKVY and the Mission Organic Value Chain Development for Northeastern India, all aimed at promoting organic farming and improving soil health. Additionally, the

Table 5. Techniques for measuring and estimating soil organic carbon (SOC) dynamics

Methods	Description	References
Traditional	SOC stock change is calculated by multiplying organic carbon with bulk density for 0-30 cm depth, using stratified sampling at 0-10 cm and 10-30 cm reported in t CO_2 eq ha^{-1}	(120)
Emerging Methods	Emerging methods like spectroscopy, eddy covariance and remote sensing reduce the cost and time of traditional carbon measurement.	(121)
Spectroscopy	Soil reflectance techniques (Vis-NIR, MIR, XRF) are cost-effective, accurate and repeatable, with data fusion enhancing results.	(122)
Eddy Covariance and Carbon Flux	Carbon flux measurement is useful for large areas but faces challenges like sensor drift and data gaps, requiring farm management data for accuracy.	(123)
Remote Sensing	Remote sensing with airborne and UAV sensors, combined with AI/ML and data fusion (e.g., Sentinel 2, UAV, GIS), enhances SOC prediction accuracy.	(124)
Electrical Conductivity	EC estimates SOC and enhances spatial accuracy with soil texture and land use, providing cost-effective precision agriculture tools.	(125)
Soil Organic Carbon Modelling	SOC models use factors like carbon inputs, climate and soil properties, with RF and XGBoost offering high accuracy, while ML and DL need large datasets.	(126)

NMSA supports agroforestry and micro-irrigation to foster sustainable farming practices. The National Adaptation Fund for Climate Change (NAFCC) assists States and Union Territories vulnerable to climate change, helping them adapt to its adverse effects. The Climate-Smart Village (CSV) initiative tests and implements climate-smart agriculture (CSA) practices at the local level, improving farmers' ability to adapt to climate change. The Pradhan Mantri Krishi Sinchayee Yojna (PMSKY) focuses on water conservation and extending irrigation coverage. The Biotech-KISAN initiative fosters partnerships between scientists and farmers to develop innovative agricultural solutions. Furthermore, the Carbon Credit Trading Scheme (CCTS), launched by the Ministry of Power, allows the trading of carbon credits to incentivize emission reductions in agriculture. India's policy landscape also includes the National Mission on Natural Farming, Andhra Pradesh Community Natural Farming (APCNF) and initiatives like the Namami Ganga Programme, which contributes to reforestation and biodiversity conservation. The National Solar Mission, which promotes solar energy and the National Mission for a Green India, which focuses on forest cover restoration, supplement these initiatives. The National Mission on Strategic Knowledge for Climate Change (NMSKCC) promotes climate science research and capacity building, whereas the National Mission for Sustaining Himalayan Ecosystems (NMSHE) works to preserve the Himalayan ecology. These activities are consistent with India's objective of generating net-zero emissions by 2070, promoting sustainable agriculture methods and minimizing the consequences of climate change.

Advantages

Carbon farming helps to mitigate climate change by sequestering CO_2 in soil and biomass through strategies such as rotational grazing, agroforestry and conservation agriculture, which reduce atmospheric carbon and increase carbon storage (127). It also benefits soil health by increasing organic carbon, strengthening soil structure and increasing fertility. Zero tillage, cover cropping and composting techniques preserve organic matter, enhance water retention and prevent erosion, making soil more robust to adverse weather (128). Furthermore, carbon farming promotes biodiversity by providing habitat for beneficial insects and pollinators, lowering pesticide use and promoting land restoration and agroecology (129). Farmers can profit economically from carbon credit markets and increased agricultural yields, which diversify income streams and improve financial resilience (130). Carbon farming promotes sustainable agriculture by lowering environmental impact, saving resources and increasing production, resulting in improved food security and economic opportunities for rural people (131).

Challenges

Carbon farming initiatives (CFIs) encounter a number of challenges, including complex scheme designs, a lack of farmer understanding and competing goals among stakeholders. Farmers face high input costs, concerns about productivity implications and the requirement for certification (132). Furthermore, political instability, insufficient skills and financial hurdles restrict participation (133). Despite financial incentives, these obstacles show that monetary rewards alone may not ensure farmer involvement in CFIs. The Green Revolution increased agricultural output while simultaneously increasing GHG emissions, which contribute to climate change. Carbon farming, including SOC storage, provides a solution by sequestering CO_2, improving soil health and promoting biodiversity (134). However, obstacles to its acceptance include high implementation costs, the requirement for specialized knowledge and varied performance between locations (135). The legislative framework for carbon farming remains fragmented, with regulatory and transparency gaps that make compliance difficult for farmers. There is an increasing desire for supportive regulatory frameworks with clear standards, incentives and support systems to promote carbon farming on a greater scale (136).

Future thrust

Carbon farming demands extensive studies of GHG emissions, including those from machinery, transportation and fertilizer production. Life-cycle analysis, particularly of nitrogen fertilizers and N_2O emissions, is critical for assessing soil carbon sequestration strategies. Policies and grassroots initiatives should address farmers' socioeconomic concerns and incentivise practices through carbon credits and carbon banks, which provide farmers with cash streams while also assisting corporations in offsetting emissions. Agroforestry practices and the use of organic-carbon fertilizers improve carbon retention and soil health. Carbon credits are in high demand worldwide, supporting renewable energy initiatives, innovation and job creation in line with the UN's SDGs.

In India, research on optimizing carbon farming using technology such as satellite monitoring and AI-based soil analysis is being undertaken and needs to be expedited. Carbon farming could contribute significantly to India's carbon reduction targets and generate $63 billion across 170 million hectares per year. Carbon credit systems offer economic incentives and regions like the Indo-Gangetic plains and the Deccan Plateau are ideal for carbon farming, while challenging regions like the Himalayan foothills require tailored solutions. Integrating organic and agro-ecological practices can boost carbon sequestration and farm resilience. Effective policy support, including targeted subsidies and technical assistance, is crucial for accelerating carbon farming adoption in India.

Conclusion

Carbon farming is a resilient method for offsetting carbon emissions through sustainable practices like agroforestry, cover cropping, rotational grazing and minimal tillage, which enhance CO_2 absorption, soil fertility and productivity. It incorporates the circular carbon economy, which enables farmers to monetize carbon credits while also promoting sustainable development. In India, CF has environmental, economic and social benefits, particularly for rural farmers, by lowering emissions and improving soil health. However, issues such as high costs and inadequate policy assistance persist. Technological advancements and policy integration may boost CF's effectiveness in combating climate change. Carbon farming, particularly agroforestry and silvipastoral systems, boosts agricultural output, food security and carbon sequestration. Despite its benefits, adoption is hampered by farmer reluctance, necessitating expert guidance and advisory services to overcome obstacles. To fully realize CF's potential, challenges related to geography, finance, policy and technology must be addressed.

Global initiatives can promote CF by offering financial incentives, technical support and carbon measurement frameworks, helping transform agriculture into a key solution for climate change.

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Authors' contributions

SG conceived the idea and wrote the manuscript. VM revised and reviewed the manuscript. TK, BP, KN, MA reviewed and finalized the manuscript. All authors read and approved the final article.

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