PLANT SCIENCE TODAY
Vol 12(sp3): 01–09
https://doi.org/10.14719/pst.8832

eISSN 2348-1900

REVIEW ARTICLE

A systematic review on carbon sequestration potential of different cropping systems in India

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Received: 12 April 2025; Accepted: 04 November 2025; Available online: Version 1.0: 31 December 2025

Cite this article: Senthilnathan S, Subasri K, Kiruthika N, Saravanakumar V, Indumathi VM, Jeyalakshmi P, Nirmala DM, Radha M, Rajendran T, Gurunathan S, Prahadeeswaran M. A systematic review on carbon sequestration potential of different cropping systems in India. Plant Science Today. 2025;12(sp3):01–09. https://doi.org/10.14719/pst.8832

Abstract

Carbon sequestration in agricultural systems presents a promising avenue for mitigating climate change, with India's vast agricultural sector offering significant potential to contribute to this global effort. This study examines the carbon sequestration potential within Indian agriculture, highlighting its relevance in the context of global greenhouse gas emissions. Through an extensive literature review, it evaluates carbon stocks and sequestration rates across major cropping systems, emphasizing the impact of soil properties, management techniques and climatic conditions. The study identifies significant practices such as integrated nutrient management, conservation agriculture, agroforestry and organic farming, which enhance carbon storage while simultaneously supporting sustainable agricultural systems. However, several challenges limit widespread adoption. These include high initial expenses, a lack of financial incentives, fragmented land ownership and water limitations. Government initiatives aimed at promoting climate-smart agriculture are explored, highlighting the necessity for improved support structures and market connections. Despite these challenges, Indian agriculture possesses substantial capacity to contribute to climate change mitigation through carbon sequestration, provided that existing barriers are addressed and sustainable practices are implemented at scale.

Keywords: carbon sequestration; carbon stocks; climate change mitigation; cropping systems; soil organic carbon

Introduction

The focus of the twenty-first century is on mitigating climate change, with global warming being a central concern. Human activities, especially the combustion of fossil fuels, have increased the concentration of greenhouse gases, such as carbon dioxide (CO_2), in the atmosphere, leading to a rise in mean global temperature and alternation in the climate system. In 2022, global CO_2 emissions reached a staggering 37.15 billion tons, with India contributing approximately 7.62 % of this total, amounting to 2.83 billion tons per year. India's per capita emissions have risen to 2 tons per year as of 2022 (1). Recognizing the gravity of the situation, the Intergovernmental Panel on Climate Change (IPCC) has set ambitious targets, advocating limiting global temperature increase to well below 2 °C above pre-industrial levels, with efforts to cap it at 1.5 °C. In alignment with these global objectives, India made significant commitments at COP26 in Glasgow in 2021. Specifically, India pledged to reduce emissions intensity per unit GDP by 45 % from 2005 levels and to derive about 50 % of its electric generation from non-fossil fuel sources by 2030 (2). Achieving these targets requires a substantial reduction of greenhouse gas emissions, as well as the removal of excess CO_2 from the atmosphere. One of the promising options for achieving this goal is carbon capture and storage (3, 4). Carbon capture and storage technologies that trap CO_2 from industrial sources and sequester it in underground geologic formations offer potential solutions. Additionally, nature-based solutions for enhancing carbon sinks such as forests and agricultural lands can offset hard-to-abate emissions (5).

Carbon sequestration refers to the natural process of capture and long-term storage of atmospheric carbon dioxide to mitigate climate change (6). Although agriculture contributes to 13 % of India's emissions, this sector holds enormous potential for reducing atmospheric carbon dioxide through sequestration in soils and vegetation (1). Adoption of recommended land management practices can increase soil organic carbon (SOC) stocks while supporting agricultural productivity and resilience. India, the world's first most populous country with over 1.4 billion people to feed, faces the twin challenges of food security and climate change adaptation and mitigation. Indian agriculture contributed 13 % of national greenhouse gas emissions in 2023, through activities such as fertilizer production, enteric fermentation in livestock, residue burning and cultivated organic soils. Simultaneously, Indian farmlands offer significant potential for carbon sequestration through changes in cropping systems, land management practices and restoration of degraded lands (7).

Globally, soils represent the largest terrestrial pool of organic carbon, estimated at 2500 gigatonnes of carbon (Gt C) in the top 3 m (6). Agricultural soils alone may contain 300 to 800 Gt C, much of which has been lost over decades of intensive farming (6). Rebuilding some of this lost soil carbon through changes in land management practices could significantly offset global CO_2 emissions. In India, total SOC stocks are estimated at 23.4 Gt in the top 1 m depth (8). Furthermore cultivated lands in India lost 25 %-50 % of their original SOC pool over a century of farming (7). Restoring a portion of this depleted carbon through sustainable land management practices could contribute to climate change mitigation while enhancing long-term soil fertility and farm productivity. Despite this potential, comprehensive reviews focusing on carbon sequestration across different cropping systems remain limited. Accordingly, this review examines the existing literature on the current status of carbon stocks and the potential additional carbon sequestration possible in major cropping systems of India. The conceptual framework of this review is illustrated in Fig. 1.

Methodology

Articles were collected from Google Scholar and Scopus using a combination of the keywords, including "carbon sequestration", "sequestration potential", "soil organic carbon", "SOC", "carbon stock", "factors influencing", "enhancing practices" and "government policies". Out of the initially collected articles (n = 984), 805 articles were excluded due to irrelevance or duplication. Relevance was determined based on the articles' focus on the specified keywords and their alignment with the study's objectives. Duplicates were screened using manual verification. After reviewing the abstracts and full texts, 119 additional articles were excluded, leaving the rest for the current study. Fig. 2 provides a preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram, illustrating the article screening process from initial search to final selection.

Cropping systems in India

India's diverse cropping systems, including food and cash crops, play a crucial role in ensuring food security and livelihood. The predominant rice-wheat cropping system, while contributing significantly to the national food basket, has led to soil quality deterioration, necessitating the introduction of short-duration crops (9). India's agricultural sector, which accounts for 18 % of GDP and employs 60 % of the workforce, is influenced by macroeconomic reforms and policies (10). The shift towards high-value crops, driven by economic growth and increased consumer demand, has implications for agricultural policies (11). The rice-wheat cropping system in India, particularly in the northwestern region, has seen

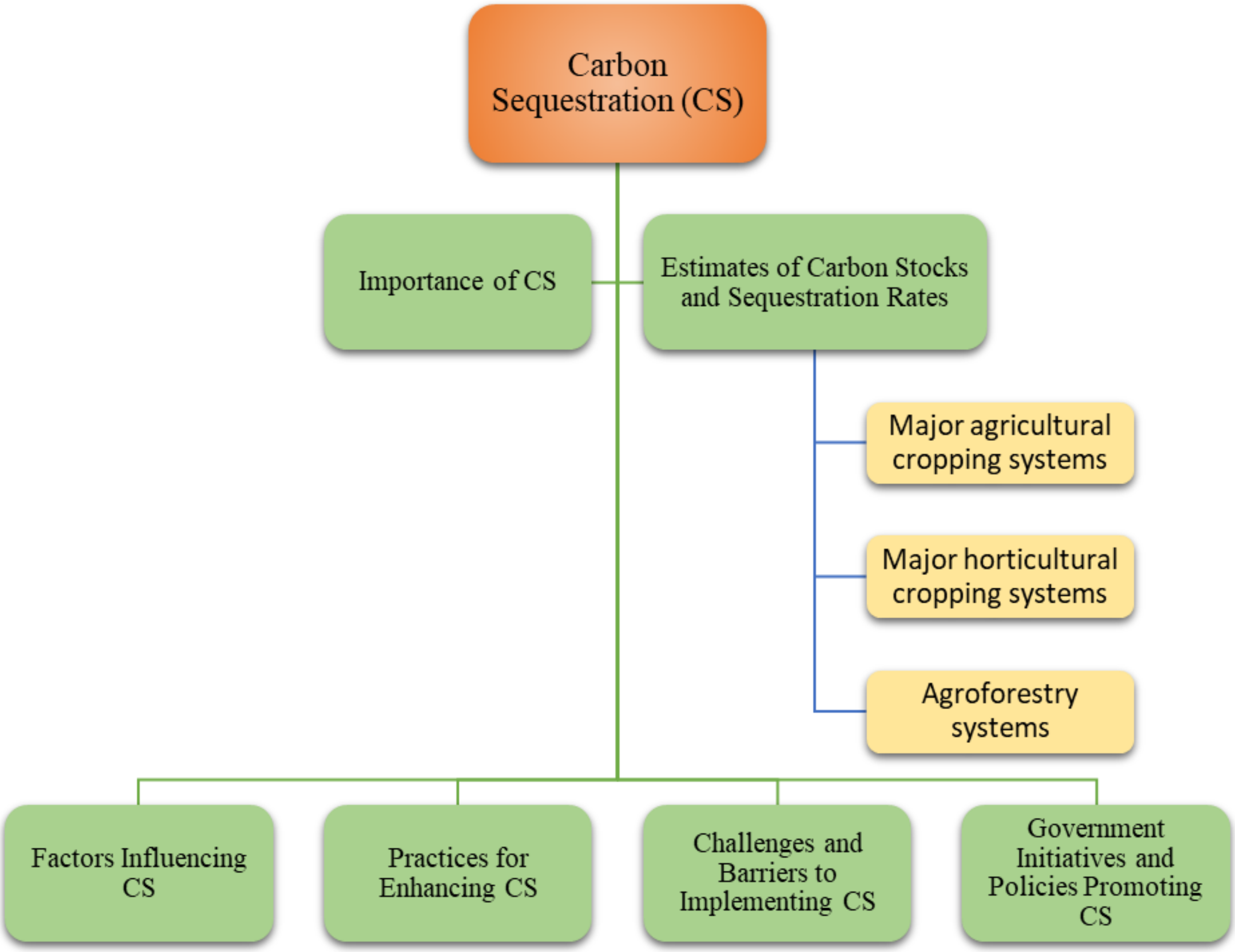

Fig. 1. Conceptual framework for carbon sequestration potential in Indian agriculture.

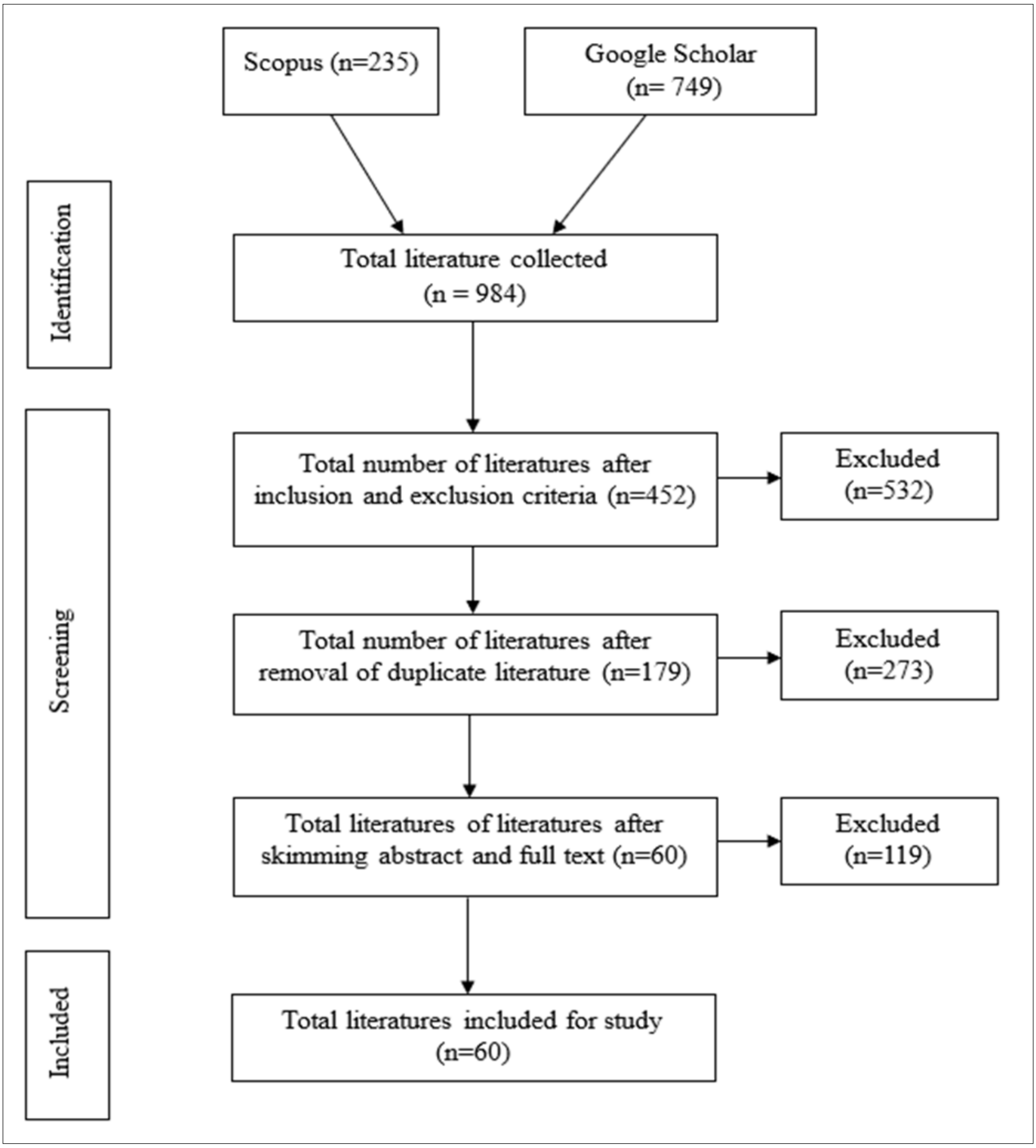

Fig. 2. PRISMA diagram depicting the systematic screening process of the article.

significant growth in the last two decades (12). However, concerns have been raised about its environmental impact and productivity (13). The introduction of new, improved varieties has made double cropping of rice and wheat possible, but traditional practices such as puddling for rice cultivation have led to soil degradation (14). Current crop residue management practices in this system are also a cause for concern, with the use of combined harvesters leading to the burning of rice straw and the need for more sustainable residue retention (15).

The cotton-pulses cropping system in India, particularly in the central and southern regions, has significantly contributed to farm incomes and the supply of cotton and pulses. Pulses, in particular, are crucial for their protein content and nitrogen-fixing properties (16). However, there are challenges in meeting the growing demand for pulses, including the need for improved seed and variety replacement rates (17). Chickpea, a key pulse crop, has seen a regional shift in production and there is a need to address the imbalance in pulse production and consumption (18, 19). The oilseeds-pulses cropping system in India, which includes crops like mustard, groundnut, sesame and soybean, play a crucial role in the country's agricultural and economic landscape (20, 21). These crops are particularly important in rainfed and resource-scarce regions, contributing significantly to the livelihood security of small and marginal farmers (20). However, there is a significant gap between the production and demand of edible oilseeds, leading to a growing dependency on imports (21). Mechanized production has been identified as a potential solution to enhance crop yield and reduce labour drudgery (22). The development of soybean, a key crop in this system, has not only contributed to India's self-sufficiency in edible oil but also holds promise for addressing pulse protein malnutrition (23).

Estimates of carbon stocks and sequestration in different cropping systems

Carbon sequestration in agricultural cropping systems

Numerous studies have evaluated the carbon sequestration potential of dominant croplands, plantations and agroforestry systems across India. Marked variability in carbon stocks and sequestration rates across major cropping systems in different agro-climatic regions of India is summarized in Table 1. Rice-based cropping systems in Telangana exhibit a wide range of soil carbon content (2.5-15 Mg C ha^{-1}) and accumulation rates (0.17-1.3 Mg C ha^{-1} yr^{-1}), attributed to factors such as soil types, water use efficiency and cropping intensity. The higher carbon storage observed in rice-wheat systems indicates the potential for further sequestration through sustainable intensification practices. Regional variations are also evident for other crops like wheat and maize, with soil carbon pools ranging from 3-6 Mg C ha^{-1} in major production zones. Intercropping of food grains with legumes has demonstrated promising results in enhancing carbon, with carbon stocks exceeding 9 Mg C ha^{-1} and sequestration rates of over 0.4 Mg C ha^{-1} yr^{-1}. These findings highlight the relevance of adopting context-specific optimization strategies through diversified, integrated farming practices.

Carbon sequestration potential in major horticulture cropping systems

Horticulture crop systems in India have shown varying degrees of carbon sequestration potential, as illustrated in Table 2. Intercropped vegetable farming in Telangana store substaintial soil carbon, with levels of approximately 7 Mg C ha^{-1}, indicating their meaningful contributions to climate change mitigation. Plantation crops such as coconut and mango are increasingly recognized as important carbon sinks, exhibiting soil carbon pools from 4 up to 41 Mg C ha^{-1} across leading States. As perennial systems with minimal disturbance, harnessing their potential through coordinated conservation efforts could deliver climate resilience.

Notably, mixed coconut and mulberry orchards in Kerala display exceptionally high carbon sequestration rates exceeding 1.8 Mg C ha^{-1} yr^{-1}, storing over 30 Mg C ha^{-1}. These rates are notably higher compared to other systems in the region, such as rice-based and vegetable farming systems. For instance, rice-based systems in Telangana show a range of 2.5-15 Mg C ha^{-1} in soil carbon content and intercropped vegetable farming in Telangana stores around 7 Mg C ha^{-1}. The superior performance of mixed coconut and mulberry orchards highlights their potential as an effective integrated agroforestry model for balancing farmer livelihoods, food security and environmental enhancement goals. The data underscores that characterizing region-specific biophysical interactions can inform locally attuned agroecosystem revitalization pathways. Blending traditional knowledge systems with modern sciences to develop innovative nature-based solutions is vital to unlock the climate change mitigation and adaptation potential of India's agricultural sector, while simultaneously strengthening rural economies.

Carbon sequestration in agroforestry systems

Large-scale agroforestry systems highlight the pivotal role of trees play in landscape-level soil regeneration. Table 3 shows that Assam's rubber plantations store over 19.4 Mg C ha^{-1}, while smaller Eucalyptus-based farms in Madhya Pradesh sequester 20 Mg C ha^{-1} yr^{-1}. Adapting profitable agroforestry approaches through participatory research and incentive mechanisms can balance ecological integrity with rural livelihood needs.

While forests require long gestation periods for significant carbon sequestration benefits, changes in agricultural land management practices can lead to faster carbon accumulation rates in the initial years (2). The croplands are estimated to have sequestered over 28 million tonnes of carbon dioxide in India in 2014 through the adoption of best management practices (5). SOC sequestration depends significantly on cropping systems, crop varieties, inputs management, tillage practices and crop residue management. Thus, agriculture and related land use changes provide a feasible negative emission strategy for India to meet its climate goals.

Factors influencing carbon sequestration potential

Parameters influencing soil organic carbon balance and sequestration potential include climate (temperature and rainfall patterns), soil properties, farm management practices and land-use changes. Soil characteristics such as texture, clay content and baseline organic carbon levels play a key role in determining the carbon storage capacity of agricultural lands. Clay-rich soils can stabilize greater amounts of organic matter and sequester carbon more rapidly than sandy soils due to their higher surface area and aggregation potential (6, 34). Additionally, soils with greater initial soil organic carbon provide a foundation for accumulating even higher levels of carbon over time through the adoption of appropriate practices. Farm management techniques such as retaining crop

Table 1. Sequestration potential and soil organic carbon stock in major cropping systems across India

Crop/cropping system	SOC stock (Mg C ha^{-1})	Carbon sequestration potential (Mg C ha^{-1} yr^{-1})	Location	Reference
Rice - rice	2.5	0.17-1.3	Telangana	(24)
Wheat	3.1-5.4	0.2-0.5	Haryana	(25)
Maize	3.6-6.2	0.4-0.8	Bihar	(26)
Rice - maize	7.51	0.22	Telangana	(27)
Maize + pigeon pea (1:3)	9.02	0.42	Telangana	
Pigeon pea + green gram (1:3)	9.52	0.41	Telangana	
Pigeon pea + groundnut (1:7)	9.24	0.39	Telangana	
Bt cotton - fallow	7.24	0.20	Telangana	
Bt cotton + green gram (1:3)	8.47	0.26	Telangana	
Soybean-mustard	5.21	0.19	Madhya Pradesh	(28)
Moong-wheat	5.09	0.18	Madhya Pradesh	
Pigeon pea	5.87	0.215	Madhya Pradesh	

Table 2. Soil organic carbon stock and sequestration potential in major horticulture cropping systems in India

Crop/cropping system	SOC stock (Mg C ha^{-1})	Carbon sequestration potential (Mg C ha^{-1} yr^{-1})	Location	Reference
Sweet corn - vegetables tomato	7.91	0.17	Telangana	(27)
Bhendi - marigold - beetroot	6.77	0.05	Telangana	
Coconut	4	0.53	Karnataka	(29)
Coconut + mulberry (*Morus* spp.)	32.8	1.80	Kerala	(30)
Mango	40.70	1.80	Uttarakhand	(31)

Table 3. Carbon sequestration potential in agroforestry systems in India

Agroforestry systems	SOC stock (Mg C ha^{-1})	Carbon sequestration potential (Mg C ha^{-1} yr^{-1})	Location	Reference
Eucalyptus	6.02	0.22	Madhya Pradesh	(28)
Eucalyptus + paddy -wheat	10.68	0.39	Madhya Pradesh	
Eucalyptus + soybean-mustard	8.62	0.31	Madhya Pradesh	
Eucalyptus + moong-wheat	9.53	0.34	Madhya Pradesh	
Eucalyptus + pigeon pea	11.64	0.42	Madhya Pradesh	
Bamboo	9.27	1.61	Tripura	(32)
Rubber	19.4	1.1	Assam	(33)

residues, using conservation tillage and balanced nutrient inputs significantly impact carbon sequestration dynamics. Leaving crop residues on the surface or incorporating them into the soil enhances carbon inputs and promotes the accumulation of SOC (35, 36). Practices such as no-tillage and reduced tillage, which minimize soil disturbance, help conserve existing soil carbon stocks by reducing losses (34, 37, 38). Adequate and balanced nutrient inputs also ensure optimal plant growth and residue production thereby increasing carbon inputs.

Previous studies indicate that climatic factors such as temperature and rainfall patterns influence carbon cycle processes (39). Higher temperatures generally accelerate the decomposition of organic matter leading to lower carbon accumulation rates. In contrast, regions with favourable rains support greater biomass production and plant residue returns, improving carbon sequestration potential. Climate changes can thus alter the balance between carbon inputs and losses, affecting net carbon storage rates. Land use changes such as deforestation and grassland conversion have major implications for carbon fluxes. Clearing forests releases large carbon stocks from biomass and soils resulting in net ecosystem carbon losses (40, 41). In contrast, the conversion of marginal lands into pastures or the integration of trees with crops through agroforestry systems can progressively increase carbon sequestration in both soil and plant biomass over time. The adoption of sustainable land management practices is thus critical for minimizing carbon losses with land-use changes, while maximizing opportunities for expanding terrestrial carbon sinks.

Practices for enhancing carbon sequestration in Indian agriculture

Many studies have evaluated practices that enhance productivity and carbon storage in Indian cropping systems. Key options include conservation agriculture (CA), integrated nutrient management (INM), agroforestry, organic farming, water management, agro-biodiversity and land restoration. CA aims to reduce soil erosion and degradation through three broad practices such as, reduced or zero tillage, retention of crop residues and crop rotations (42). In northwest India, CA is mainly adopted in rice-wheat cropping through zero-till sowing of wheat into untilled soil and rice residues after rice harvest. It can significantly increase SOC stocks while reducing production costs (43). Meta-analysis of Indian studies shows average SOC gains of 2.2 Mg C ha^{-1} (0-0.3 m depth) after 5 years of CA practice in rice-wheat (34). Century model estimates 0.51 Mg C ha^{-1} yr^{-1} sequestration in rice-wheat with full CA adoption in Haryana (8). However, high crop residue requirements for CA (8-10 Mg ha^{-1} for the rice-wheat system) pose adoption challenges. Farm machinery access issues, burning bans and residue market distortions affect uptake. Long-term SOC gains are not guaranteed without sustained inputs (44).

Balanced application of chemical fertilizers along with organic sources such as manure, vermicompost and biofertilizers has synergistic benefits (45). INM builds SOC, improves soil health and reduces nitrous oxide emissions compared to inorganic fertilizers alone. Returning crop residues such as leaves, stems and roots to agricultural fields protects soil from erosion and provides carbon inputs to enhance SOC stocks. Removing residues for feed, fuel or other uses reduces this protective cover and nutrient recycling capacity (6). Improved technologies and policies for on-farm utilization can increase adoption. Modelling 14 long-term experiments found that residue removal decreased SOC stocks 0.48 Mg C ha^{-1} yr^{-1} across corn-based systems in the USA (46). Integrating trees and shrubs into agricultural landscapes through practices like alley cropping, boundary plantations or silvipasture can provide significant carbon sequestration in soils and biomass (47, 48). Deep tree roots and litter deposition enhance SOC stocks compared to open cultivated lands (49, 50). Complex interactions occur between soils, crops and trees affecting overall productivity (51). A global meta-analysis of 90 sites found an average SOC gain of 0.26 Mg C ha^{-1} yr^{-1} after land use change from cropland to silvipasture (52). However, competition for resources such as water, nutrients and light can reduce crop yields under some tree-crop combinations and require careful design optimization (51). Also, the time lag for agroforestry to accumulate carbon stock increases initial opportunity and maintenance costs (53).

Previous studies observed that organic agriculture aims to enhance soil health and quality over the long term by relying on ecologically based cultural practices (54). Key features such as reduced synthetic chemical input use, application of compost, manure and cultivation of green manures and cover crops could increase SOC stocks (55). Resource efficiency and ecological resilience are found to improve, but transitional yield declines may occur in intensive systems (56). However, organic nutrient sources are often limited and unpredictable in quantity. Productivity drops in initial years pose short-term income risks requiring transitional support policies. Certification costs impede widespread adoption by smallholder farmers.

Importance of carbon sequestration in mitigating climate change

Carbon sequestration plays a crucial role in mitigating climate change by removing CO_2 from the atmosphere and storing it in various natural reservoirs. As the concentration of CO_2 in the atmosphere continues to rise due to human activities such as burning fossil fuels and deforestation, it is essential to find effective ways to reduce these emissions and prevent further warming of the planet. Carbon sequestration offers a promising solution by capturing and storing carbon dioxide, thereby reducing its impact on the climate.

Carbon sequestration enhances carbon sinks and offsets emissions from difficult-to-decarbonize sectors (57). The cost of sequestering 1 t CO_2 through land-management practices is estimated at USD 20–50 t^{-1} CO_2, which is lower than that of engineered solutions (58, 59). In India, the economic mitigation potential from agriculture is estimated at 25–30 Mt CO_2-eq yr^1 at a cost of USD 20 t^1 CO_2-eq, largely driven by changes in rice and wheat production systems. Carbon sequestration also provides significant co-benefits, including improved soil health, higher farm yields and increased farm income (6, 60). Moreover, it buys time for an economy-wide transition towards low-carbon pathways across sectors (5).

Various projections depict the substantial potential of carbon sequestration globally and for a populous agrarian country like India. An IPCC estimate suggests that 89 % of cost-effective CO_2 mitigation through 2030 can come from agriculture (61). As per India's intended nationally determined contributions (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC), it has been proposed to create an additional carbon sink of 2.5-3 billion tonnes of CO_2 through enhanced forest and tree cover by 2030. Harnessing this cumulative potential by adopting practices that augment carbon storage and reduce GHG emissions can enable India to support climate change amelioration.

Challenges and barriers to implementing carbon sequestration practices

Switching to new practices like zero tillage, permanent bed planting and agroforestry requires investments in specialized equipment, land preparation, saplings, seeds and labour, which are often unaffordable for small and marginal farmers who constitute 86 % of agricultural landholders in India (62, 63). High costs of laser land levelling equipment (Rs 3-6 lakhs), direct seeders, residue management tools and water-efficient irrigation systems, have limited adoption only to well-off farmers so far. Smallholders lacking access to formal credit get locked out of making large initial investments, hampering the adoption of capital-intensive practices.

Carbon sequestration is an externality that farmers do not get compensated for, in the current scenario. Carbon pricing policies are still nascent in India (7). Low awareness among farmers about the global warming potential of agriculture and potential benefits from carbon markets and trading schemes restricts participation. Complicated registration and eligibility criteria pose entry barriers for smallholders in participating in existing voluntary carbon trading platforms (7). The average farm size in India is only 1.08 ha compared to the USA's 168 ha. Miniaturization of holdings increases fragmentation. Small parcels limit mechanization, equipment-sharing arrangements, adoption of boundary, field plantations and agroforestry (43).

High transaction costs for aggregators in pooling produce from numerous smallholders, reduce incentives to invest in low-carbon practices. Overexploitation of groundwater for irrigation in North-Western India is leading to rapid depletion, increasing pumping costs (64). This discourages adoption of water-intensive practices. Rainfed regions with limited access to irrigation and low water retention capacity of soils limit the adoption of management options requiring assured water supply (43). Lack of farmer awareness, training and extension services on specific techniques like residue retention, composting, mulching, zero tillage and bio-fertilizers application constraint adoption. Scientific expertise and technical guidance on implementing climate-smart practices suited for local conditions are often lacking (7). Removing crop residues from fields for fodder, fuel, etc. leaves soils exposed and vulnerable to erosion (65). But farmers have few alternatives.

Incorporating residues jeopardizes important co-benefits such as organic manure for smallholders who cannot afford chemical fertilizers. Weak land tenure security discourages long-term investments in land improvement and carbon sequestration practices (7). Lack of access to markets, farm inputs and extension services due to missing institutions and infrastructure (43). Lack of holistic climate policies creating the right incentives for adoption of carbon sequestration practices.

Government initiatives and policies promoting carbon sequestration in agriculture

The Government of India has introduced several programs and initiatives to encourage climate-smart agricultural practices that boost carbon sequestration in both soil and biomass. Government policies and socioeconomic conditions influence the adoption of carbon-friendly techniques. Incentives like payments for ecosystem services, input subsidies and technical support can encourage sustainable methods such as conservation agriculture or agroforestry among smallholder farmers (66). Additionally, land tenure security and access to credit are critical for enabling the long-term investments required for soil carbon restoration.

A comprehensive approach that considers policy, technical and socioeconomic factors is vital to realizing the potential for carbon sequestration. The National Initiative on Climate Resilient Agriculture (NICRA) is an Indian government project that promotes climate-resilient farming technologies, including those that enhance carbon sequestration. As part of this initiative, various climate-resilient farming technologies are being tested across 100 climate-vulnerable districts, focusing on soil, water, nutrients, crops, livestock and forestry (26). A carbon balance study was conducted using the EX-ACT model in three villages in the Nalgonda and Khammam districts of Andhra Pradesh.

The National Mission for Sustainable Agriculture (NMSA), under India's national action plan on climate change, aims to develop innovative agricultural practices and strengthen farming communities' ability to cope with climate variability and change (67). Government initiatives like the National Programme for Organic Production (NPOP) launched in 2000 and the National Project on Organic Farming (NPOF) introduced in 2004 aim to promote organic farming and increase carbon sequestration (68).

The National Agroforestry Policy (NAP), introduced in 2014, promotes agroforestry to enhance tree cover on farmlands and increase carbon sequestration. This policy plays a vital role in reducing rural poverty, revitalizing the wood-based industry and integrating food production with environmental services, while also contributing to India's goal of achieving 33 % forest and tree cover and mitigating greenhouse gas emissions from agriculture (69).

The National Action Plan on Climate Change (NAPCC) includes carbon management strategies aimed at mitigating climate change through forest management and enhancing carbon sequestration in vegetation (70). Under the Paramparagat Krishi Vikas Yojana (PKVY), clusters receive support from regional councils for Participatory Guarantee Scheme (PGS) certification of organic farming practices. Since 2015-16, this scheme has promoted organic agriculture through the development of PGS-certified organic clusters (71). Although current government initiatives have raised awareness, providing financial incentives, improving market linkages and reinforcing support mechanisms are essential to encourage the widespread adoption of carbon sequestration practices.

Conclusion

Indian agriculture holds substantial potential to contribute to global climate change mitigation through enhanced carbon sequestration, owing to its vast agricultural lands and diverse cropping systems. This review highlights the considerable opportunities for improving carbon stocks in soils through practices such as conservation agriculture, integrated nutrient management, agroforestry and organic farming. These practices not only enhance carbon storage but also deliver multiple co-benefits, including improved soil health, increased agricultural productivity and enhanced resilience to climate change. However, the widespread adoption of these carbon-sequestering practices faces several challenges. High initial costs limited financial incentives, fragmented landholdings, water scarcity and gaps in farmer knowledge are significant barriers that need to be addressed (Fig. 3). Additionally, the lack of robust carbon markets and effective compensation mechanisms for farmers further limits the large-scale implementation of sustainable practices. Overcoming these obstacles will require a coordinated and sustained effort from policymakers, researchers, extension services and farmer organizations.

Government initiatives like the National Initiative on Climate Resilient Agriculture (NICRA), the National Mission for Sustainable Agriculture (NMSA) and the National Agroforestry Policy (NAP) provide a policy framework for promoting climate-smart agricultural practices. However, further efforts are required to strengthen financial incentives, improve market linkages and expand technical and institutional support to farmers. A multifaceted approach, involving the development of carbon markets, investment in agricultural research and capacity building for farmers will be crucial in scaling up successful carbon-sequestration practices. In conclusion, leveraging the carbon sequestration potential of Indian agriculture offers a vital opportunity not only to mitigate climate change. but also, to ensure food security, improve rural livelihoods and promote sustainable development. By adopting region-specific and context-sensitive strategies and fostering cross-sectoral collaboration, India can emerge as a leader in climate-smart agriculture and contribute to a more sustainable and resilient global food system.

Authors' contributions

SS conceptualized the study and critically prepared the manuscript. SK conducted the literature review and contributed to the introduction and methodology. KN handled data analysis and visualization. SV edited the manuscript and ensured coherence across sections. VMI reviewed and enhanced sustainable practices. JP ensured English editing. NDM prepared tables and figures. RM contributed to sections on barriers and challenges. RT ensured technical clarity and logical flow. GS coordinated team efforts and PM coordinated the overall work and approved the final manuscript as the corresponding author.

Compliance with ethical standards

Conflict of interest: The Authors of This paper declares no conflict of Interest.

Ethical issues: None

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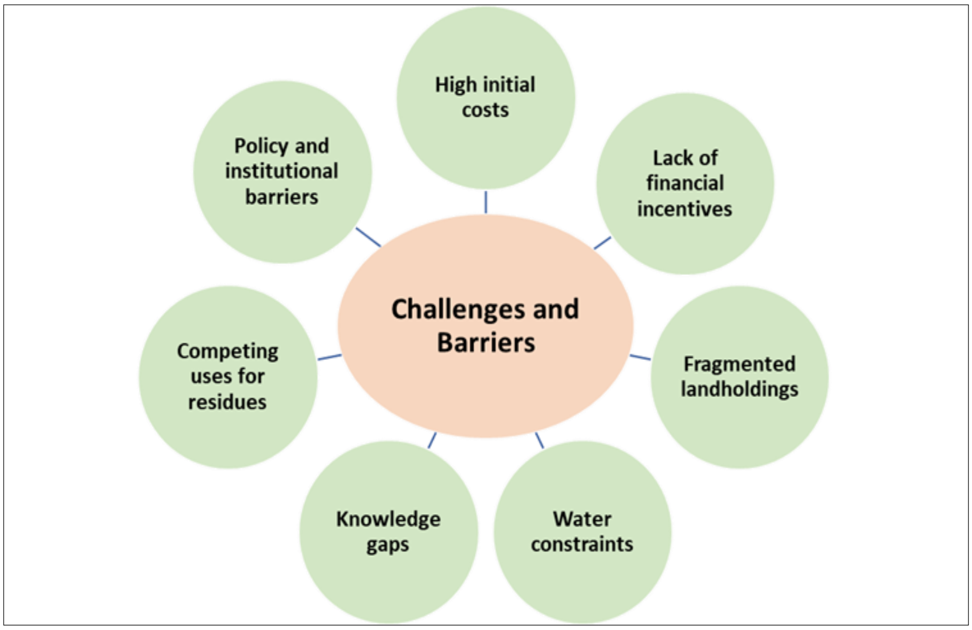

Fig. 3. List of challenges and barriers to implementing carbon sequestration practices.

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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