



From agronomic practices to carbon credits: A systematic review of agricultural carbon markets in India

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Abstract

Carbon markets are becoming an important tool for reducing greenhouse gas (GHG) emissions from agriculture and they are particularly relevant for India, which is both the world's third-largest GHG emitter and a major agricultural economy. This systematic review synthesises current evidence on the development, mechanisms and emerging trends of carbon markets in Indian agriculture, situating them within the wider global context. Following a Preferred reporting items for systematic reviews and meta-analyses (PRISMA)-guided search of five databases (247 records identified, 62 studies retained), the review examines five closely connected areas: global and India-specific carbon market mechanisms; agronomic practices that enable market participation; major agricultural GHG sources and mitigation opportunities; soil health and carbon sequestration; and methodological, policy and inclusion gaps. The synthesis demonstrates that sustainable practices such as conservation agriculture, alternate wetting and drying (AWD) in rice systems, biochar application, precision nutrient management and agroforestry can reduce agricultural emissions while also improving soil fertility and carbon storage. Furthermore, emerging tools, including blockchain-based transparency systems and AI-enabled precision agriculture, can strengthen market credibility and make participation more accessible for smallholder farmers. However, agricultural carbon markets in India remain at an early stage and their growth is constrained by weak measurement, reporting and verification (MRV) systems, inadequate smallholder inclusion, concerns around additionality and the lack of a comprehensive domestic regulatory framework. Uncertainties around carbon permanence, leakage, transaction costs and market volatility further temper these prospects and warrant cautious interpretation of reported gains. This review identifies four priority areas for future work: standardising robust MRV systems, developing integrated impact models, designing inclusive market mechanisms and aligning carbon market policies with India's broader agricultural, climate and livelihood commitments. Addressing these gaps will be essential for realising agriculture's mitigation potential and supporting a low-carbon, climate-resilient agricultural future in India.

Keywords: agronomic practices; biodiversity co-benefits; carbon markets; greenhouse gas emissions; Indian agriculture; soil carbon sequestration

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1. Introduction

Agriculture occupies a central yet complex position in the global response to climate change. While it is a major source of greenhouse gas (GHG) emissions, it also offers significant opportunities for emission reduction and carbon sequestration in soils and biomass. This dual role is particularly important for India, the world's third-largest GHG emitter in terms of total annual emissions, where agriculture is fundamental to food security, rural livelihoods and the well-being of

more than 1.4 billion people. As India pursues a more climate-resilient and sustainable agricultural system, carbon markets are emerging as a potential mechanism for incentivising agricultural mitigation and linking farm-level climate action with broader climate and sustainable development goals. Financial incentives for verified emission reductions and carbon removals facilitate the alignment of field-level practices with national and global climate objectives. Although agricultural carbon markets in India remain in the early stages of development, their significance is growing. Currently, more than 50

voluntary carbon farming projects operate in states such as Haryana and Madhya Pradesh, promoting regenerative and climate-smart practices such as no-tillage, AWD in rice fields, intercropping, micro-irrigation and agroforestry. However, India has not yet established a comprehensive domestic regulatory framework for agricultural carbon markets. As a result, many projects continue to depend on voluntary mechanisms and international standards, including methodologies developed by Verra. Current evidence suggests that voluntary carbon credit trading could reduce agricultural emissions in India by as much as 84 % by 2070 under a scenario of widespread adoption of climate-smart practices relative to a business-as-usual baseline (1); the assumptions underlying this projection are discussed further where the estimate is used. However, these opportunities must be viewed alongside continuing pressures from economic growth, rising energy demand and agricultural expansion, all of which continue to shape India's carbon emissions profile (2).

Globally, carbon pricing instruments such as carbon taxes and emissions trading systems (ETS) have helped reduce industrial emissions and encourage more sustainable production practices. Compared with these established systems in developed economies, India's agricultural carbon market remains relatively new (3). Even so, emerging technologies are beginning to expand what these markets can achieve: artificial intelligence (AI), precision agriculture and blockchain-based transparency systems can improve monitoring, reduce information gaps and make carbon market participation more practical and trustworthy for smallholder farmers (4, 5). At the same time, international evidence shows that carbon-aligned farming practices can strengthen soil health and improve the long-term sustainability of farming systems. Natural climate solutions, including improved agricultural management, could contribute more than one-third of the cost-effective mitigation needed by 2030 to remain consistent with the 2 °C climate target (6).

Despite growing interest in agricultural carbon markets, the existing literature remains fragmented and does not yet provide an integrated understanding of how carbon market design, agronomic mitigation practices, soil carbon dynamics, measurement, reporting and verification (MRV) system requirements and equity concerns interact in Indian agriculture. Recent studies have examined individual issues, such as the technical potential of agricultural carbon credits, the eligibility of conservation agriculture, or the yearly performance of carbon farming projects in India, but these studies typically treat carbon farming practices and carbon market mechanisms as separate rather than interdependent concepts and often treat inclusion, additionality, permanence, farmer payments, monitoring systems and policy design as separate concerns. As a result, there is a clear gap in evidence that connects field-level practices with market credibility, smallholder

participation and long-term environmental integrity in the Indian context. Unlike prior reviews, which have generally examined carbon market mechanisms, agronomic mitigation practices, or MRV and equity issues in isolation, this review addresses that gap by moving beyond descriptive reporting of carbon market initiatives. It synthesises recent global and India-specific evidence to connect market mechanisms with field-level practices, greenhouse gas mitigation pathways, soil health outcomes, institutional requirements and farmer inclusion. In doing so, the study advances current knowledge by identifying which agricultural practices are the most market-ready, where methodological uncertainty remains and how targeted interventions can improve scientific credibility, social inclusion and long-term environmental integrity in India's emerging agricultural carbon market. Against this background, this systematic review aims to address the research gap by:

- A) Examining the current status, mechanisms and emerging trends of agricultural carbon markets globally and in India
- B) Identifying key agronomic practices that can support carbon sequestration, greenhouse gas mitigation and farmer participation in carbon markets
- C) Assessing major agricultural GHG emission sources, their drivers and the mitigation potential of market-based interventions
- D) Evaluating how soil health, soil organic carbon sequestration and sustainable land management can strengthen agricultural carbon credit systems
- E) Identifying the main methodological, policy and inclusion gaps that must be addressed to build credible, equitable and scalable agricultural carbon markets in India.

2. Methods

Literature search and study selection

This systematic review was conducted following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to identify and synthesise evidence on carbon markets in agriculture, with particular emphasis on Indian agriculture, agronomic practices for reducing carbon emissions and soil carbon sequestration. A structured literature search was carried out across five databases - Springer, Elsevier (ScienceDirect), Web of Science, Scopus and Google Scholar - to ensure broad coverage of environmental science, agricultural systems, climate policy, soil science and sustainability research. The search covered records published between 2013 and 2025 and was conducted on January –April 2026.

Search terms were developed around four core themes: carbon markets, agriculture, agronomic practices for reducing carbon emissions and soil carbon

sequestration. The main search strings combined terms such as “carbon markets”, “carbon credits”, “voluntary carbon markets”, “agriculture”, “Indian agriculture”, “agronomic practices”, “greenhouse gas mitigation”, “carbon emission reduction”, “soil carbon sequestration”, “soil organic carbon”, “conservation agriculture”, “biochar”, “alternate wetting and drying”, “precision nutrient management” and “agroforestry”. These terms were used in different combinations to capture both global evidence and India-specific studies relevant to agricultural carbon market development. The search identified 247 records. Following title and abstract screening, 143 records were excluded and 104 full-text articles were assessed for eligibility; a further 42 articles were excluded because they were not relevant to agriculture ($n=18$), lacked a clear carbon market focus ($n=14$), or provided insufficient methodological detail ($n=10$). A total of 62 articles were retained for the final synthesis (Fig. 1). Title and abstract screening and full-text eligibility assessment were carried out by the review team and disagreements were resolved through discussion.

Data extraction and thematic coding

A structured data extraction framework was used to capture key information from each included article.

Extracted variables included author and year of publication, geographical focus, study type, carbon market mechanism, agricultural practice assessed, greenhouse gas or soil carbon sequestration outcome, measurement or verification approach, policy relevance and major findings. Particular attention was given to agronomic practices that contribute to emission reduction or carbon storage, including conservation agriculture, AWD, crop residue management, biochar application, precision nutrient management, cover cropping and agroforestry.

The extracted evidence was coded thematically according to the main objectives of the review. Coding categories were developed inductively from the five review objectives and comprised global and Indian carbon market mechanisms, agronomic practices for mitigation and market participation, agricultural GHG emission sources and drivers, soil carbon sequestration and methodological, policy and inclusion gaps. Coding was performed manually by the review team and consistency was checked through cross-review of a sample of coded articles. This thematic structure enabled comparison across diverse study types while maintaining alignment with the scope of the review.

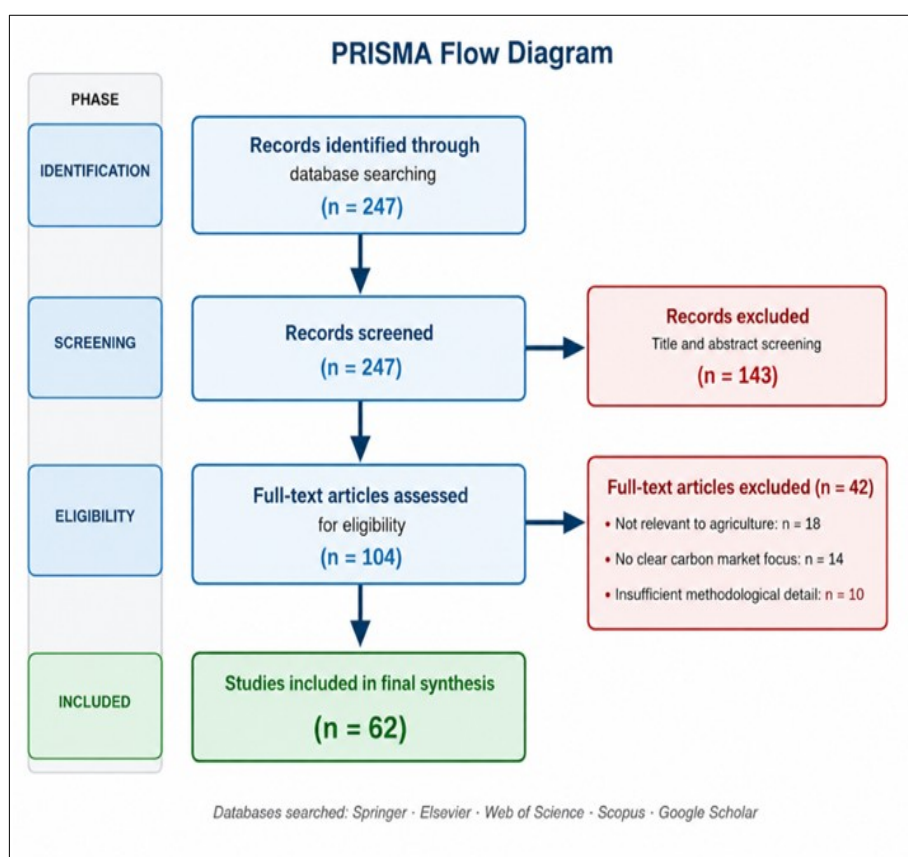


Fig. 1. PRISMA flow diagram showing identification, screening, eligibility assessment, exclusion and final inclusion of studies used in the systematic review.

Synthesis approach

Given the diversity of study designs, geographical contexts, carbon accounting methods and outcome indicators, a narrative thematic synthesis approach was adopted. Evidence was grouped by theme and interpreted across agricultural practices, emission pathways, carbon sequestration mechanisms and carbon market readiness. Quantitative findings reported in the literature, such as emission reduction percentages and soil organic carbon gains or sequestration rates, were used to describe indicative performance patterns rather than to generate pooled statistical estimates.

A formal meta-analysis was not conducted because the included studies varied substantially in research design, spatial scale, baseline assumptions, measurement duration and reporting of uncertainty. Statistical pooling under these conditions could have produced misleading estimates and reduced the interpretive value of the review. Instead, the synthesis prioritised methodological transparency, contextual interpretation and identification of consistent patterns across the evidence base.

Quality assessment and limitations

Study quality was assessed qualitatively against four predefined screening criteria: relevance to Indian or comparable agricultural systems, clarity of methods, a demonstrable connection to carbon markets or agricultural mitigation and sufficiency of outcome reporting. The main limitation of this review is the heterogeneity of the available literature. Differences in carbon accounting methods, soil sampling depth, time scale, emission factors, modelling assumptions and market design features limited direct comparison across studies. The absence of a formal quality-appraisal tool means that study quality could not be used to weight the interpretation of findings. Nevertheless, the selected evidence provides a robust basis for understanding the current state of agricultural carbon markets, the role of agronomic practices in reducing emissions and the methodological and policy gaps that must be addressed to scale credible carbon market systems in Indian agriculture.

3. Results and Discussion

Global carbon markets - mechanisms and comparative lessons

Carbon markets allow governments, companies and other actors to meet climate targets by trading emission allowances or verified carbon credits. Although these markets are well established in industrial sectors, their application in agriculture remains more limited and

complex; major systems in China, the European Union, California, Australia and the United Kingdom show that market design varies widely across regions (7, 8). The global carbon market is now valued at more than US\$175 billion annually, but agriculture still occupies a relatively small position within the system. Bringing agriculture more fully into carbon markets is challenging because emission reductions and carbon removals must be measured across diverse soils, climates, crops and farm management systems. Issues such as additionality, permanence, leakage, transaction costs and smallholder inclusion therefore remain central to agricultural carbon market design (9–11).

Country-level experiences

Country-level experiences offer useful lessons and insights about carbon market systems for India. The European Union does not directly include agriculture in its emissions trading system, but it encourages offset-based support for climate-smart farming (12). Australia's Emissions Reduction Fund demonstrates how regulated sectors can purchase agricultural offsets and create new income opportunities for farmers, although project distribution has often favoured lower-cost landscapes (9).

China's carbon trading pilots show the importance of strong institutions, technology, adoption and clear regulatory capacity when scaling carbon markets (10, 13). International discussions under Article 6 of the Paris Agreement are also pushing countries towards more harmonised crediting rules, which may influence how agricultural carbon credits are developed and traded in the future (14–16).

As shown in Fig. 2, the global carbon market was highly concentrated in 2023, with the European Union Emissions Trading System (EU ETS) accounting for 87 % of the €881 billion market value, while other major ETSs held much smaller shares. Overall, carbon pricing instruments covered 28 % of global GHG emissions, highlighting the growing role of market-based mechanisms in climate mitigation.

Blockchain technologies and market transparency

Digital technologies are becoming increasingly important in carbon market governance. Blockchain can improve transparency by creating traceable and tamper-resistant records of carbon credit generation, transfer and retirement. For Indian agriculture, where farms are small and carbon projects may involve thousands of participants, such tools could help reduce information gaps and improve trust in certification (17, 18). However, blockchain is not a solution on its own; its value depends on the quality of the underlying field data, the strength of MRV systems and the ability of farmers and institutions to use digital platforms effectively (19, 20).



Global carbon market share by ETS system, 2023

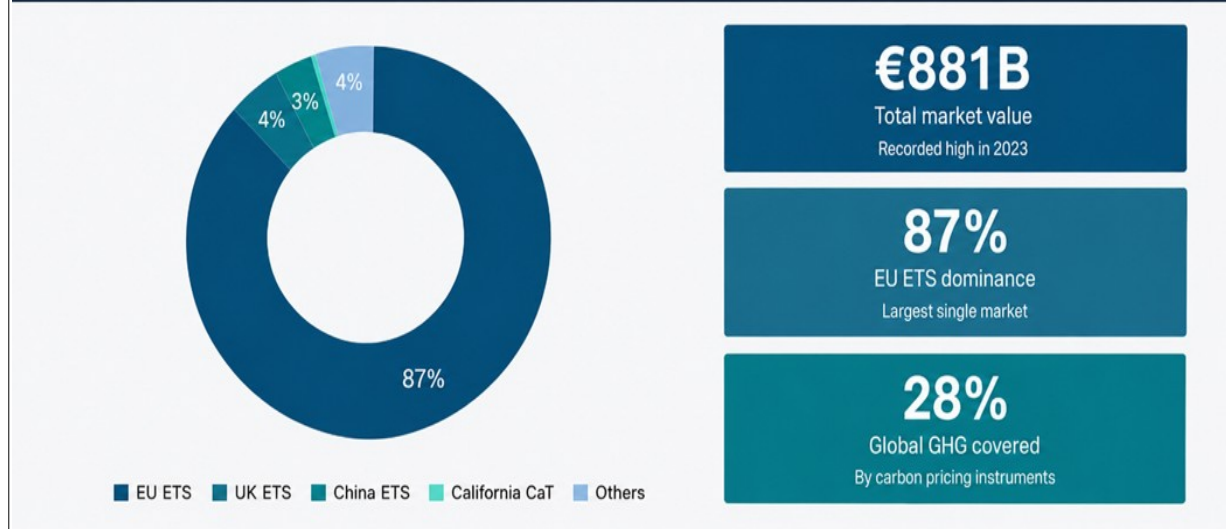


Fig. 2. Global carbon market share by major emissions trading systems (ETS) in 2023.

Carbon markets in Indian agriculture: current state and emerging trends

Existing initiatives and policy framework

India's agricultural carbon market is still emerging, but voluntary projects have expanded rapidly in recent years. More than 50 active carbon farming projects now promote practices such as no-tillage, AWD in rice, intercropping, reduced chemical fertiliser use, micro-irrigation and agroforestry. However, the evidence also shows that current participation is uneven. Larger landholders and better-connected farmers are more likely to benefit, while smallholders, women farmers, tenant farmers and marginalised groups remain under-represented. Concerns also remain around additionality, because some practices may have been adopted before project enrollment and permanence, because farmers may discontinue practices when incentives are weak or project support ends (21). These practices are relevant because they can reduce emissions or increase carbon storage while also supporting broader improvements in farm management. Furthermore, the implementation of such regenerative approaches facilitates a shift in the agricultural sector from a net emission source to a significant carbon sink, potentially offsetting substantial portions of national industrial output (21).

India's policy environment provides a useful foundation, but it is still fragmented. Programmes such as the National Mission for Sustainable Agriculture, Paramparagat Krishi Vikas Yojana, PM-Kisan and Pradhan Mantri Fasal Bima Yojana (PMFBY) can support the adoption of sustainable agricultural practices. At the same time, India does not yet have a fully developed domestic regulatory system for

agricultural carbon credits. As a result, many projects depend on voluntary standards and international methodologies were developed (22). Recent government efforts to develop a voluntary carbon market framework for agriculture indicate growing policy interest, but credible implementation will require clear rules for measurement, verification, farmer benefit-sharing and long-term monitoring (14).

Emerging trends and new market mechanisms

India's earlier experience with Clean Development Mechanism projects helped build familiarity with market-based climate governance (23, 24). Current efforts are shifting toward domestic carbon trading systems, voluntary carbon market frameworks and project models that better reflect Indian farming conditions. Emerging technologies such as artificial intelligence, remote sensing, digital farm records and precision agriculture may improve monitoring and reduce transaction costs. However, the practical success of these tools will depend on whether they can be adapted to small farm sizes, limited credit access, uneven digital literacy and infrastructure constraints in rural areas. The establishment of India's Carbon Credit Trading Scheme (CCTS) and voluntary carbon market initiatives provides a strong institutional foundation for expanding agricultural carbon projects in the coming years. Nevertheless, the widespread adoption of AI-enabled monitoring, remote sensing and digital MRV systems will require targeted investments in rural digital infrastructure, farmer capacity building and affordable financing mechanisms to ensure the inclusion of smallholder farmers. A timeline of key milestones in carbon trading system is depicted in Fig. 3.

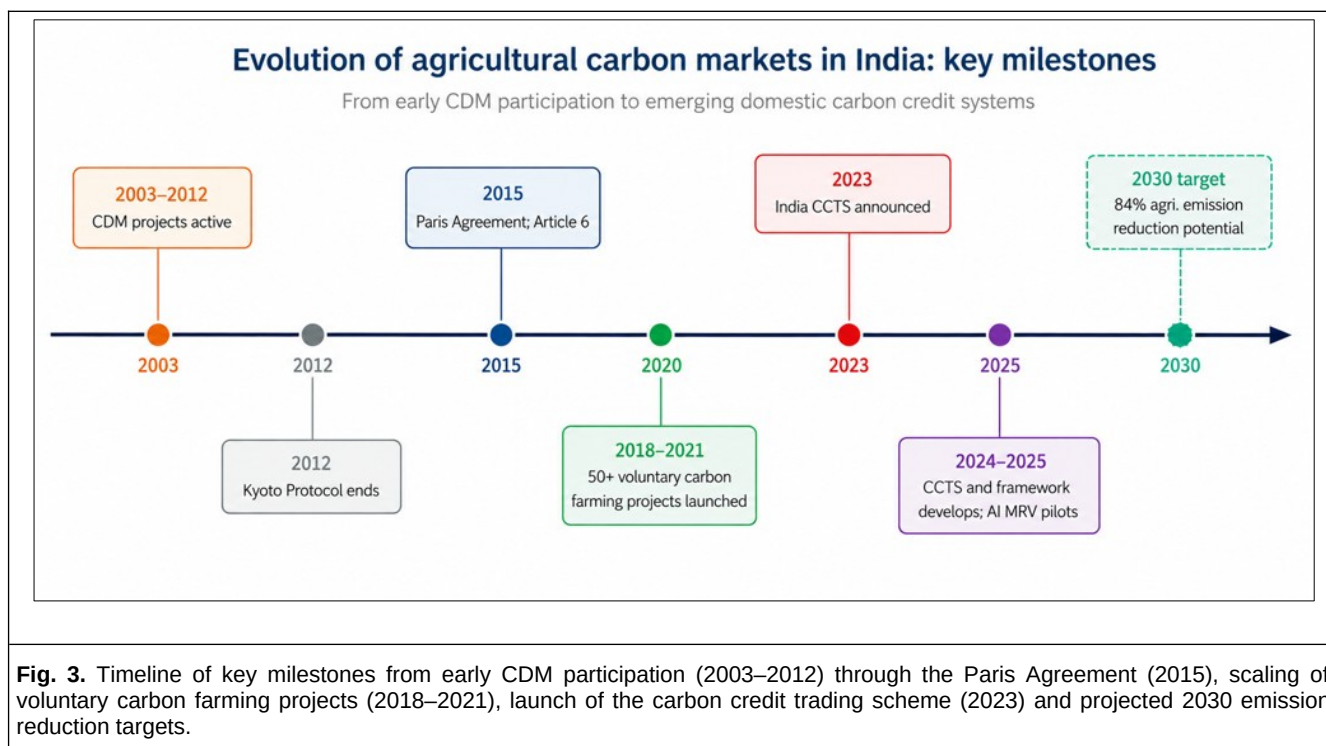


Fig. 3. Timeline of key milestones from early CDM participation (2003–2012) through the Paris Agreement (2015), scaling of voluntary carbon farming projects (2018–2021), launch of the carbon credit trading scheme (2023) and projected 2030 emission reduction targets.

Agronomic practices in carbon sequestration and market participation

Agricultural carbon credits ultimately depend on what happens at the field level. Practices must either reduce greenhouse gas emissions or increase carbon storage in a way that can be measured, verified and maintained over time. The reviewed studies show that several agronomic practices are relevant for carbon market participation in India, including conservation agriculture, precision nutrient management, water-saving rice cultivation, cover crops and green manuring, crop residue management, biochar application, climate-smart cropping systems and agroforestry. Their suitability for carbon markets depends not only on mitigation potential, but also on additionality, permanence, cost, ease of monitoring and farmer adoption.

Conservation agriculture: zero tillage, residue retention and crop diversification

Conservation agriculture (CA), defined by minimum soil disturbance, permanent organic soil cover and diversified crop rotations, is one of the most extensively studied and scalable pathways to soil organic carbon (SOC) accumulation. Under zero-tillage (ZT), disruption of soil aggregates is eliminated, reducing the oxidation of previously protected organic matter and stimulating stable aggregate formation that physically protects carbon (25). A second-order global meta-analysis synthesising over 25000 paired observations confirmed SOC gains of 9–13 % over conventional tillage under no-till with residue retention, strongly modulated by climate, soil texture and cropping history (25). In Indian conditions, long-term trials on Indo-Gangetic Plain soils demonstrate that ZT wheat following puddled transplanted rice can accumulate 0.15–0.30 Mg C ha⁻¹ yr⁻¹ under adequate residue return (25).

From a carbon market perspective, ZT presents tractable MRV pathways because tillage practice is satellite-detectable; the primary additionality challenge is that ZT adoption has advanced substantially through agronomic extension programmes independent of carbon finance (22). Crop diversification within CA systems—particularly legume inclusion—lowers N₂O emissions by 8–12 % relative to mono-cropped systems (26).

Cover crops and green manuring

Cover crops contribute to soil carbon through biomass addition, erosion suppression and stimulation of mycorrhizal networks. A widely cited meta-analysis estimated a mean SOC increase of 6 % from cover crop adoption, although a methodologically stricter review revised this downward to approximately 0.03 Mg C ha⁻¹ yr⁻¹, underscoring sensitivity to biomass production, termination timing and soil type (27, 28). Green manuring with *Sesbania aculeata* Pers. and *Crotalaria juncea* L. in Indian rice-based systems has demonstrated SOC increases of 8–15 % in South Asian long-term experiments, with concurrent improvements in soil bulk density and water-holding capacity (29). For carbon markets, the low and variable sequestration rates of cover crops present additionality and permanence challenges; when combined with no-till and residue retention in bundled agronomic packages, their incremental contribution becomes more robustly attributable under portfolio-based carbon methodologies (30).

Agroforestry systems

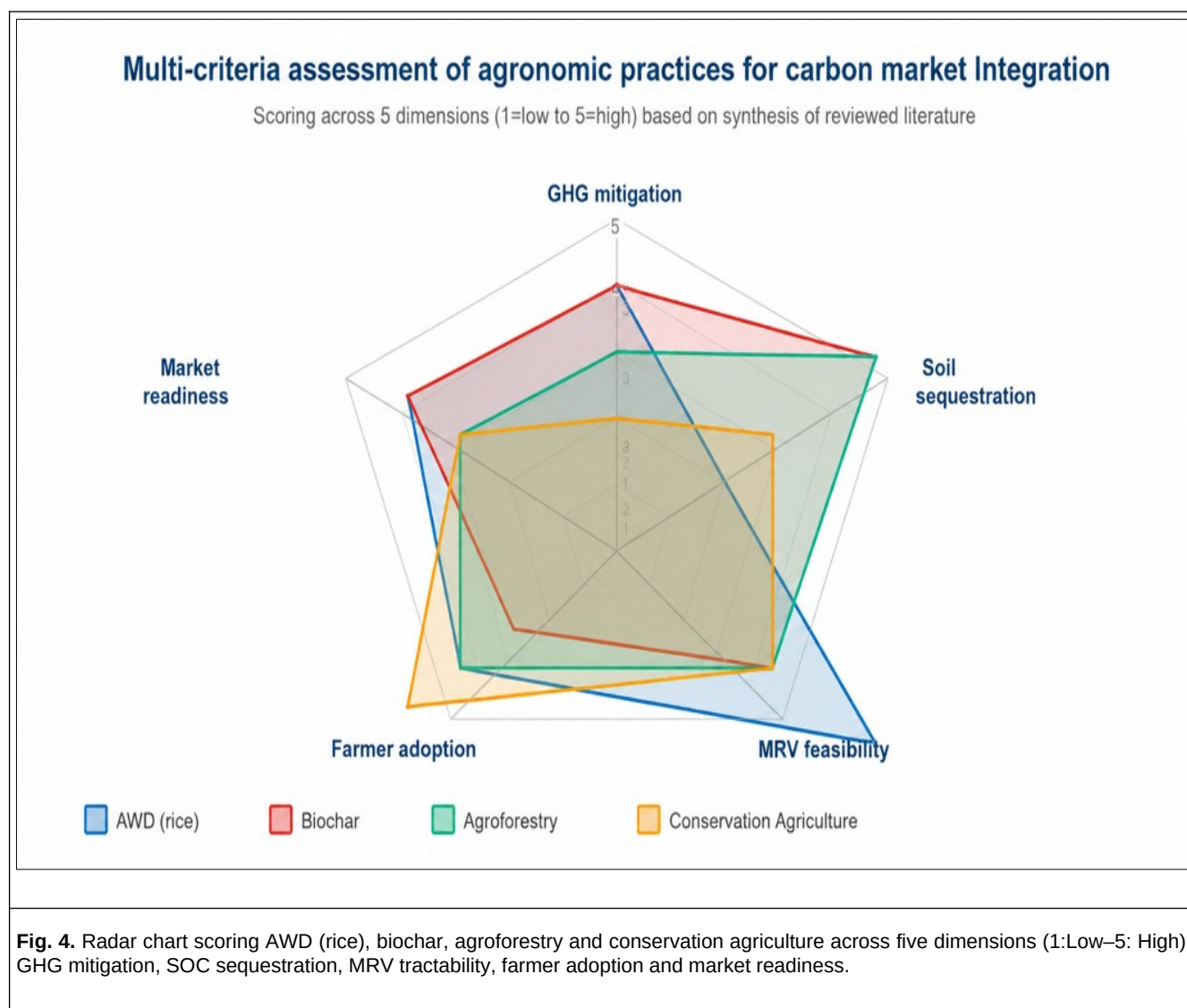
Agroforestry offers one of the strongest long-term carbon sequestration opportunities because it stores carbon in tree biomass, roots and soil. Reported sequestration rates vary by species, climate, planting

density and management, but tropical and subtropical systems can provide substantial carbon gains (25). India's National Agroforestry Policy has created an enabling policy environment and state-level models in Andhra Pradesh, Gujarat and Tamil Nadu show that tree-based farming can be adapted to different production systems. The main barriers for carbon market integration are high upfront costs, delayed returns, land tenure concerns, timber regulations and the need for low-cost allometric models suited to Indian species (29). Despite its substantial carbon-storage potential, agroforestry faces greater crediting complexity because of long-term permanence requirements, monitoring needs and land-tenure considerations.

Synthesis–agronomic practices and carbon market suitability

The reviewed evidence shows substantial variation in the readiness of agronomic practices for carbon-market participation. The AWD and biochar have comparatively stronger near-term potential because their mitigation pathways are relatively well characterised and crediting approaches are more developed. Conservation agriculture, residue management, precision nutrient

management and agroforestry also offer considerable mitigation potential but face greater challenges related to baseline establishment, additionality, permanence, attribution and MRV. Climate-smart cropping systems may provide broader mitigation and resilience benefits, but their bundled nature makes project-level attribution more complex. These differences demonstrate that market readiness should not be assessed solely by mitigation potential; credible MRV, additionality, permanence, cost-effective verification and farmer adoption are equally important. In India, practice-based or portfolio approaches that recognise complementary practices may improve MRV efficiency, reduce transaction costs and make carbon-market participation more feasible for smallholders. They would also help avoid narrow crediting models that reward one practice without considering the broader farm system (30). Fig. 4 scores AWD, biochar, agroforestry and conservation agriculture across GHG mitigation, SOC sequestration, MRV tractability, farmer adoption and market readiness, while Fig. 5 maps these practices by mitigation potential and MRV tractability to identify those ready for near-term scaling.



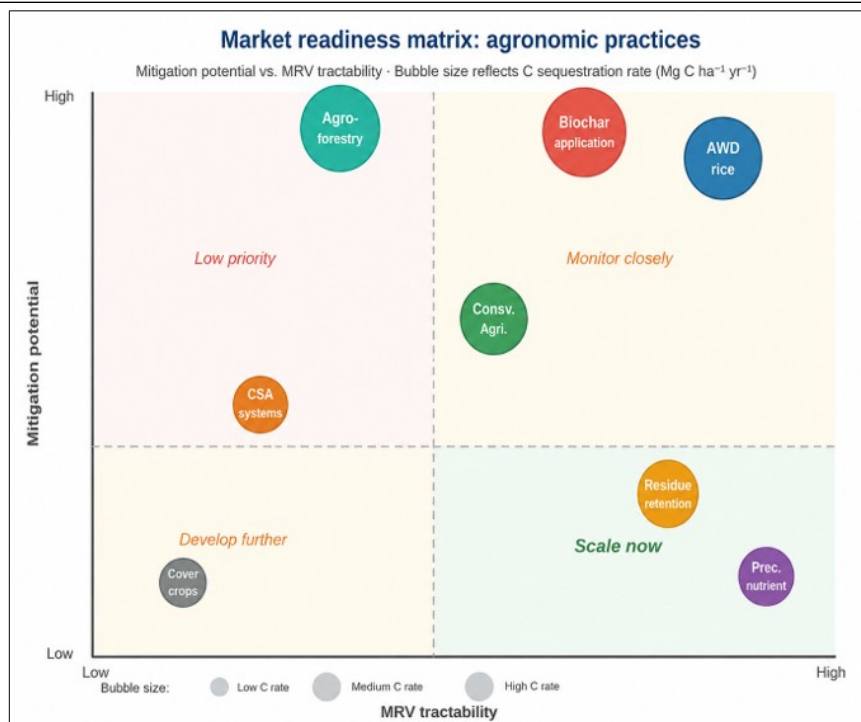


Fig. 5. Market readiness matrix for agronomic practices in Indian agricultural carbon markets. Practices are plotted by mitigation potential (y-axis) and MRV tractability (x-axis). Bubble size reflects estimated carbon sequestration rate ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$). AWD and biochar occupy the high-priority 'scale now' quadrant.

Precision nutrient management and fertiliser-use efficiency

Nitrous oxide (N_2O)-with a 100-year global warming potential approximately 273 times that of CO_2 -is the dominant GHG from agricultural soil management globally. Precision nutrient management (PNM) addresses excess nitrogen through synchronisation of nutrient supply with crop demand using soil testing, leaf colour charts, optical sensors and variable-rate application technologies. In India, neem-coated urea has documented N_2O reductions of 18–30 % in irrigated rice-wheat systems and Green Seeker and Nutrient Expert tools in Tamil Nadu and Andhra Pradesh have reduced nitrogen inputs by 20–25 kg N ha^{-1} per season without yield penalties. Direct-seeded rice can also lower methane emissions compared with puddled transplanted rice in regions such as Punjab and Haryana (29). A global meta-analysis demonstrated that site-specific nutrient management reduces N_2O emissions by 21–38 % while improving nitrogen use efficiency (NUE) by 15–25 % (31). For carbon markets, N_2O abatement through PNM is theoretically attractive because emission factors are codified in Intergovernmental Panel on Climate Change (IPCC) Tier 2 and Tier 3 methodologies; however, the high spatial and temporal variability of soil denitrification makes ex-ante quantification challenging (30, 32). Despite its high mitigation potential, field-level variability and measurement requirements make its crediting pathway more complex than that of practices with more directly observable mitigation outcomes.

Water-saving practices – alternate wetting and drying, direct seeded rice and micro-irrigation

Flooded rice systems are a major source of methane emissions, making water-saving rice practices especially important for agricultural carbon mitigation. Alternate wetting and drying (AWD) reduce methane formation by periodically introducing aerobic soil conditions. Evidence shows that AWD can substantially reduce methane emissions compared with continuous flooding while also saving irrigation water. These practices are particularly relevant for carbon markets because approved crediting approaches already exist for methane reduction in rice systems, making AWD one of the more market-ready interventions for Indian agriculture (32, 33). Thus, AWD currently offers a comparatively clear pathway from measurable mitigation to carbon-credit generation, although consistent implementation and MRV remain essential.

Crop residue management and avoidance of residue burning

Open-field burning of crop residues in the Indo-Gangetic Plain releases an estimated 0.11–0.17 Tg CH_4 and 8.6–10.5 Tg CO_2 -equivalent annually from India alone (29). Avoidance of burning and *in-situ* residue retention deliver a dual benefit: elimination of combustion emissions and the restoration of organic carbon and nutrients to the soil. Straw return raises SOC by a mean of 12.8 % across global cropping systems, consistent with long-term straw return data from North China upland crops that estimated a sequestration rate of 0.29 $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ (34, 35). The sequestration sink saturates after

approximately 12 years of continuous incorporation—a constraint that must be accounted for in long-term carbon crediting methodologies. Happy Seeder technology, diffused across approximately 1.8 million hectares in Punjab and Haryana with Government of India subsidy support, demonstrates that policy-compatible mechanical solutions exist. Satellite-detectable fire events provide robust counterfactual evidence of prior burning, making residue retention a high-additionality practice in burning-prone geographies (22).

From a carbon-market perspective, the relevant metric for biochar is net carbon removal rather than the increase in soil carbon alone. The lifecycle assessment should account for emissions from feedstock collection and transport, pyrolysis energy, biochar processing and application and any opportunity costs associated with alternative uses of the biomass. Where residues would otherwise remain in the field, be used as fodder, or serve another productive function, diverting them to biochar production may create additional emissions or foregone carbon benefits. Therefore, carbon-crediting methodologies should quantify the net climate benefit across the full production chain, rather than crediting soil-carbon gains in isolation. This distinction is particularly important for India, where feedstock availability, transport distances, energy sources and competing uses of agricultural residues vary substantially across production systems.

Biochar provides another promising pathway because it converts crop residues into a stable form of carbon that can remain in soil for long periods. Global evidence shows that biochar can increase soil organic carbon and reduce net greenhouse gas emissions (27). Indian studies using rice husk, bagasse, cotton stalk and other residues report improvements in soil carbon over multi-year trials (29). From a carbon market perspective, biochar is attractive because of its relatively high permanence and emerging premium value in voluntary markets. Thus, although biochar has relatively high permanence and market potential, its actual carbon-credit value depends on demonstrating positive net carbon removal after accounting for the complete lifecycle of feedstock collection, production, transport and application. However, wider adoption will require reliable feedstock supply, safe production systems, farmer training and aggregation models that make participation feasible for smallholders.

Climate-smart cropping systems

Climate-smart cropping systems combine multiple practices rather than relying on a single intervention. Diversified rotations, drought-tolerant varieties, reduced tillage, organic amendments, efficient irrigation and improved nutrient management can reduce emission intensity while strengthening resilience. Evidence from dryland India suggests that millet-based systems can have lower emission intensity than irrigated rice monocultures and can improve resilience in water-limited regions (36, 37). For carbon markets, these systems may

be best captured through portfolio-based crediting models that reward combined emission reductions and soil carbon gains across the whole farm system.

Therefore, the GHG mechanisms, mitigation potential, MRV tractability and market readiness of these practices are summarised in Table 1.

Agricultural GHG emissions: sources, drivers and mitigation potential

Key emission sources and influencing factors

Agriculture is a significant contributor to global GHG emissions, primarily through CH₄, N₂O and CO₂, originating from livestock production, soil and nutrient management, energy use in controlled environments and land-use practices. The Food and Agriculture Organization of the United Nations Statistics (FAOSTAT) database documents that agriculture contributed approximately 10–12 % of global anthropogenic GHG emissions during 2001–2010, with the share rising substantially when land-use change is included (38). Food systems as a whole contribute approximately 26 % of global anthropogenic GHG emissions, with animal-based foods carrying the highest emission intensities (39). A global evaluation demonstrates substantial regional heterogeneity in agricultural GHG emissions, reflecting differences in production intensity, institutional capacity and policy implementation (40). A global meta-analysis shows that manure-based nutrient management generally increases N₂O and CH₄ emissions compared to synthetic fertilisers, with magnitudes varying with soil texture, temperature, moisture and cropping systems (31). Enteric fermentation is the dominant livestock emission source (41). Land degradation-affecting approximately 23 % of global ice-free land area—further contributes to net GHG emissions through reduced soil carbon sink capacity (42). Energy consumption for heating, cooling and lighting is the dominant CO₂ source in greenhouse agriculture (43). Indicative GHG source composition and mitigation strategies are summarised in Tables 2 and 3.

Overall, the evidence indicates that mitigation potential alone does not determine agricultural carbon-market readiness. Alternate wetting and drying and biochar currently show relatively stronger pathways towards near-term crediting because their mitigation mechanisms are comparatively well defined and relevant crediting methodologies are more advanced. Residue management and conservation agriculture also offer substantial potential, particularly where baseline practices can be clearly established, whereas precision nutrient management, cover crops, climate-smart cropping systems and agroforestry face greater challenges related to spatial variability, attribution, permanence, or monitoring costs. Thus, market readiness depends on the combined feasibility of quantifying mitigation, demonstrating additionality, ensuring permanence, implementing credible MRV and controlling transaction costs. In the Indian context, practice-specific and system-level approaches are likely to be more appropriate than a uniform carbon-crediting framework.



Table 1. Summary of agronomic practices for carbon sequestration and carbon market participation in Indian agriculture

Practice	GHG mechanism	Mitigation potential	MRV tractability	Market readiness	Key India evidence
CA / Zero tillage	SOC accumulation; reduced aggregate disruption	9–13 % SOC gain (25)	Moderate (satellite)	Moderate	0.15–0.30 Mg C ha ⁻¹ yr ⁻¹ (25) crop diversification lowers N ₂ O emissions by 8–12 % (26)
Cover crops / green manuring	SOC; BNF; N ₂ O reduction	0.03–0.15 Mg C ha ⁻¹ yr ⁻¹ (28).	Low–Moderate	Low–Moderate	8–15 % SOC (29)
Agroforestry	Above-/below-ground biomass + SOC	0.5–3.0 Mg C ha ⁻¹ yr ⁻¹ (25)	Moderate (allometric models)	Moderate	National Agroforestry Policy 2014; Indian state-level models (29)
Biochar	Recalcitrant C; N ₂ O suppression	39–41 % SOC; 34–67 % net GHG reduction (27)	Moderate	High (premium) (30)	12–28 % SOC; TN, MH (29)
Soil nutrient management	N ₂ O abatement	21–38 % N ₂ O reduction (31)	Moderate-High (IPCC Tier 2/3)	High	18–30 % N ₂ O reduction (29)
AWD (rice)	CH ₄ suppression via intermittent aerobic conditions	45–53 % CH ₄ reduction (32, 33)	High (approved methodology) (32, 33)	High (approved)	Validated in TN, Odisha and WB (32, 33)
Residue retention / burn avoidance	Combustion avoidance; SOC restitution	12.8 % SOC mean gain (34)	High (fire satellite)	High	0.29 Mg C ha ⁻¹ yr ⁻¹ (35)
CSA cropping systems	Emission intensity reduction; diversification	0.2–0.4 kg CO ₂ e kg ⁻¹ grain (36)	Moderate	Moderate	Millet systems (36,37); dryland India

Note: AWD: alternate wetting and drying; BNF: biological nitrogen fixation; CA: conservation agriculture; CSA: climate-smart agriculture; GHG: greenhouse gas; MH: Maharashtra; MRV: measurement, reporting and verification; N₂O: nitrous oxide; SOC: soil organic carbon; TN: Tamil Nadu; WB: West Bengal.

Table 2. Comparison of major agricultural greenhouse gas sources and global mitigation strategies

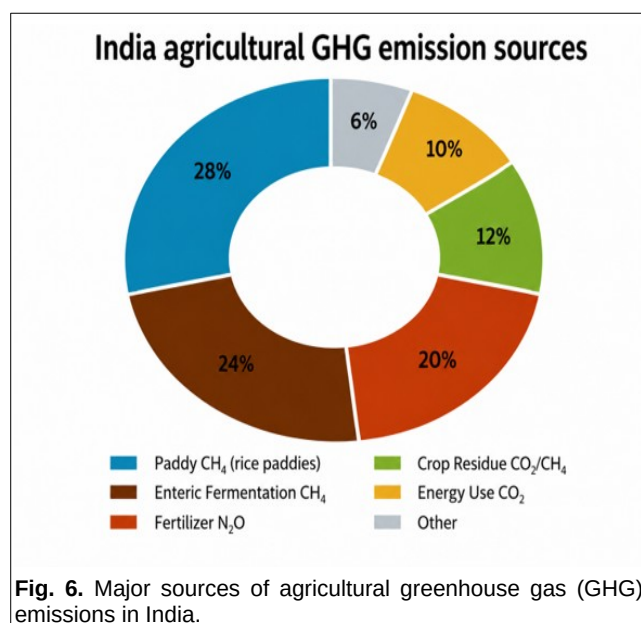
GHG source	Main gas	Key drivers	Mitigation strategies	Relevant references
Residue burning	CO ₂ , CH ₄ , N ₂ O	Open-field burning of crop residues	Residue retention, Happy Seeder technology, in-situ incorporation	(22, 32, 34)
Flooded rice systems	CH ₄	Anaerobic soil conditions, continuous flooding, residue incorporation	Alternate wetting and drying, direct seeded rice, improved water management	(29, 32, 33)
Soil nutrient management	N ₂ O	Nitrogen fertiliser, manure application, soil moisture	Precision nutrient management, improved fertiliser timing, organic–mineral nutrient balancing	(31, 32)
Greenhouse agriculture energy use	CO ₂	Heating, cooling, lighting, fossil energy dependence	Renewable energy integration, energy-efficient climate control	(44)
Enteric fermentation	CH ₄	Ruminant livestock, feed quality, herd structure	Improved feed quality, herd management, productivity gains	(45)

Note: CH₄: methane; CO₂: carbon dioxide; N₂O: nitrous oxide.

Table 3. Agricultural greenhouse gas sources and mitigation strategies for India and Tamil Nadu

Context	Major emission source	Priority mitigation strategy	Carbon market relevance	References
Indo-Gangetic Plain	Residue burning emissions	Burning avoidance and residue retention	Strong additionality where satellite-detected burning history is available	(29)
India	Nitrous oxide from nutrient use	Precision nutrient management and neem-coated urea	Relevant where fertiliser-use data and emission factors can support MRV	(29, 31, 32)
India	Flooded rice methane	Alternate wetting and drying and direct seeded rice	High market readiness because methane-reduction methodologies are relatively advanced	(29, 32, 33)
Tamil Nadu	Rice and irrigated cropping emissions	AWD, micro-irrigation, nutrient optimisation	Suitable for pilot projects where field monitoring and farmer aggregation are feasible	(29, 32, 33)
Dryland India	Emission intensity from water-stressed cropping	Millets, diversified rotations, climate-smart cropping systems	Moderate readiness; better baseline and outcome monitoring are needed	(36, 37)

Fig. 6 presents the relative contribution of major agricultural activities to greenhouse gas (GHG) emissions in India. The distribution highlights the dominant role of methane emissions from rice cultivation and livestock production, indicating substantial opportunities for emission reduction through climate-smart agricultural practices, improved nutrient management and sustainable livestock systems. Accordingly, the pathway from an emission source to a carbon credit depends on four linked steps: identifying the emission source, implementing a measurable mitigation practice, quantifying the resulting reduction against a credible baseline and verifying the outcome through an appropriate MRV system.

**Fig. 6.** Major sources of agricultural greenhouse gas (GHG) emissions in India.

Emission reduction potential of carbon markets

Carbon markets seek to internalise the climate externalities of agriculture by monetising verified emission reductions and removals. A seminal synthesis estimated that global agriculture could mitigate 5.5–6.0 Gt CO₂-equivalent yr⁻¹ by 2030 through a portfolio of practices spanning soil carbon management, livestock feed improvements and energy efficiency (44). More recent analyses demonstrate that carbon pricing can reduce agricultural emissions when policy design ensures

sectoral specificity and institutional enforcement (40). The effectiveness of market-based mitigation depends critically on additionality, with strong additionality potential through improved manure and fertiliser management (31). Targeted feed quality improvements could reduce livestock emission intensity (41). For greenhouse agriculture, renewable energy integration and precision climate control can achieve persistent CO₂ reductions, making these systems comparatively suitable for market-based mitigation (43). High mitigation potential does not necessarily imply immediate carbon-crediting feasibility. Crediting requires measurable and verifiable emission reductions, demonstrable additionality, appropriate baselines, manageable MRV costs and safeguards for permanence and leakage.

Measurement, reporting and verification – additionality, permanence and leakage

The credibility of agricultural carbon markets depends critically on robust MRV frameworks. Agricultural emissions are characterised by spatial and temporal variability, complicating baseline establishment and increasing uncertainty in credit quantification (41). Permanence remains a central concern for soil carbon sequestration; soil emission responses are sensitive to climate, management continuity and soil characteristics, implying that credited reductions may be reversible (31). Leakage further constrains mitigation integrity; without comprehensive policy alignment, emission reductions in regulated regions may be offset by increased emissions elsewhere (40). In India, the prevalence of irrigated rice systems suggests significant long-term CH₄ reduction potential through AWD if permanence safeguards are embedded in market methodologies (32).

Soil health, carbon sequestration and sustainable land management

Effects of carbon market-relevant practices on soil carbon sequestration

Soil organic carbon (SOC) sequestration was identified as a critical pathway for both agricultural sustainability and global climate mitigation over two decades ago (45). Carbon markets remunerate practices that increase net SOC or reduce net agricultural GHG emissions, including organic and mineral fertilisation

strategies, reduced or zero tillage, cover crops, residue retention, diversified rotations, biochar application and perennial systems. Climate-smart soils offer a pivotal contribution to both food security and climate stabilisation through improved management of organic inputs, tillage and residue retention (46). The '4 per mille' initiative posits that a 0.4 % annual increase in global SOC stocks could theoretically offset global fossil fuel emissions, though realising this potential requires targeted action across diverse agro-ecological contexts. The saturation concept holds that mineral-associated (stable) SOC pools have a finite storage capacity set by clay/silt surface area, so sequestration rates diminish and plateau as soils approach saturation; many degraded or low-SOC Indian soils remain well below saturation and thus retain higher near-term sequestration potential (47). Soil carbon has been identified as a priority natural climate solution, with a global technical potential of 1.85 Gt CO₂-equivalent yr⁻¹ (48). The soil-carbon outcomes, additional co-benefits and key limitations of the main carbon market-relevant soil management practices are summarised in Table 4.

A global, spatially explicit meta-analysis estimated that improved cropland management could sequester 0.28–0.43 Gt C yr⁻¹ globally, with higher potentials in low-yield, low-SOC regions (49). Climate-smart agriculture practices significantly increased SOC: biochar (+39 %), cover crops (+6 %) and conservation tillage (+5 %), with stronger effects under warmer climates (27). A second-order meta-analysis confirmed that SOC losses from land conversion can be partially restored through no/reduced tillage, residue retention, organic amendments and biochar, yielding SOC gains of 9–35 % depending on practice (25). Straw return raised SOC by a mean of 12.8 % across global cropping systems (34); long-term straw return experiments in North China upland crops estimated a sequestration rate of 0.29 Mg

C ha⁻¹ yr⁻¹ (35). In Indian conditions, biochar, integrated nutrient management, residue retention, no-till, rotations and intercropping significantly increase SOC, with practices both technically feasible and economically profitable (29). Meta-analyses report that crop-residue incorporation raises soil N₂O emissions by roughly 6–50 % (varying with incorporation method, C:N ratio and climate) even as it builds SOC, so climate benefits from full residue retention are partly offset by higher N₂O; shallow incorporation or higher-C:N residues mitigate this (31).

Fig. 7 compares the estimated percentage increase in SOC stocks and reduction in GHG emissions associated with selected agronomic practices, based on midpoint values reported in global meta-analyses. Conservation agriculture, residue retention and cover cropping provided moderate improvements in SOC accumulation and emission reduction. Overall, the results indicate that integrated adoption of these practices can enhance carbon sequestration while reducing agricultural greenhouse gas emissions, thereby supporting climate-smart and sustainable agricultural systems.

Although soil carbon sequestration has substantial mitigation potential, translating SOC gains into credible carbon credits remains challenging. Permanence may be affected by saturation and reversal following changes in farm management, while MRV is constrained by spatial variability in SOC, sampling requirements and monitoring costs. Crediting also requires demonstration of additionality and sustained farmer adoption of carbon-enhancing practices. In India, small and fragmented holdings, heterogeneous soils, climatic variability and limited field-level monitoring infrastructure further increase the cost and complexity of reliable soil-carbon crediting.

Table 4. Summary of carbon market-relevant soil management practices and their outcome

Practice	Soil/carbon outcome	Additional benefits	Key limitation	References
No/reduced tillage with residue retention	Improves SOC through reduced disturbance and residue inputs	Better soil structure and reduced erosion	Additionality may be difficult where adoption is already widespread	(22, 25, 29)
Agroforestry	Carbon storage in biomass, roots and soil	Biodiversity, shade, diversified income	Delayed returns and land-tenure or timber-policy barriers	(25, 29)
Biochar	Stable carbon addition and improved SOC persistence	Improved soil fertility and water retention	Feedstock supply, production cost and quality control	(27, 29)
Cover crops and green manuring	Moderate and variable SOC gains	Nutrient cycling, erosion control, biological nitrogen fixation	Low and context-dependent sequestration rates	(27, 28, 49)
Integrated nutrient management	Improves SOC and can reduce N ₂ O when nitrogen use is optimised	Yield stability and improved nutrient-use efficiency	Requires reliable farm-level nutrient records	(31, 32, 49)

Note: N₂O: nitrous oxide; SOC: soil organic carbon.



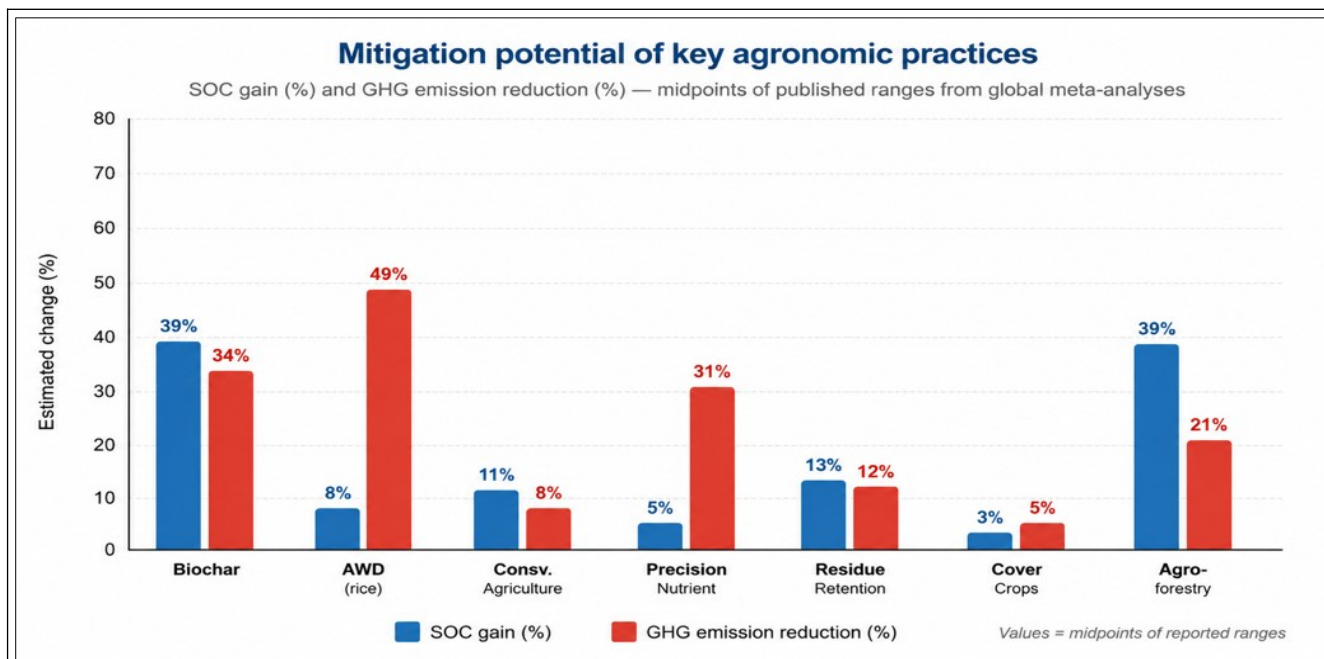


Fig. 7. Comparative mitigation potential: SOC gains (%) and GHG emission reductions (%) for key agronomic practices, based on midpoints of ranges reported in global and India-specific meta-analyses.

Implications for soil fertility and productivity

SOC is fundamental for soil structure, nutrient cycling and water retention. A large meta-analysis of Chinese cropland best management practices showed that mineral fertiliser combined with organic inputs delivered the largest gains—SOC increased by 30.6 % and yield by up to 79.8 %—with optimal results in arid regions, alkaline soils and initial SOC below 10 g kg⁻¹ (50). Important trade-offs emerge: methodologically stricter estimates of cover crop SOC benefits approach just 0.03 t C ha⁻¹ yr⁻¹ and cover crops reduced main-crop grain yield by approximately 4 % unless legume-non-legume mixtures were used, which increased yield by approximately 13 % (28, 51). These findings underscore that fertility and productivity benefits are strongly contingent on species choice, biomass and system design.

Biochar showed the highest SOC enhancement (30–41 %) followed by organic amendments (20–35 %) and perennial grasslands (18–29 %). No/reduced tillage and straw return produced moderate SOC gains, while cover crops showed comparatively smaller but positive effects. Overall, the Fig. 8 highlights the strong potential of organic inputs and reduced soil disturbance for building soil carbon and supporting climate-smart agriculture. Global assessments suggest focusing on low-SOC, low-yield, nutrient-limited soils to maximise both soil fertility and sequestration benefits, aligning with India's food security and climate objectives (49). Long-term Indian studies indicate that conservation agriculture and agroforestry can sustain SOC gains over several years to decades, although continued management is essential for maintaining carbon stocks. Droughts, floods and other climate extremes can reduce biomass

inputs and increase carbon losses, making agricultural carbon permanence conditional rather than absolute. Droughts and floods reduce biomass/residue inputs and can accelerate SOC mineralisation and erosion losses, making climate extremes a recognised reversal risk that MRV frameworks address via buffer pools or insurance-linked safeguards (52, 53).

Sustainable land management practices for carbon markets

For carbon markets to genuinely support soil health and conservation, they must prioritise management packages that deliver durable SOC gains, maintain or increase yields and minimise non-CO₂ GHGs. National-scale evidence from China demonstrates that policy-driven increases in organic inputs led to measurable SOC increases of approximately 140 kg C ha⁻¹ yr⁻¹ in topsoil over three decades without undermining production, directly relevant to the design of credible, outcome-based soil-carbon market frameworks in India (54).

Critical research gaps and methodological limitations

Scientific gaps include uncertainties in soil-carbon measurement, permanence, additionality and the limited availability of long-term, field-validated Indian data. Market-design challenges include inconsistent MRV methodologies, uncertain carbon pricing, high transaction costs and limited integration between carbon-crediting systems and India's agricultural institutions. Socioeconomic barriers include small and fragmented holdings, limited farmer awareness, high participation costs, weak aggregation mechanisms and concerns regarding equitable benefit sharing, particularly for women and marginalised farmers.

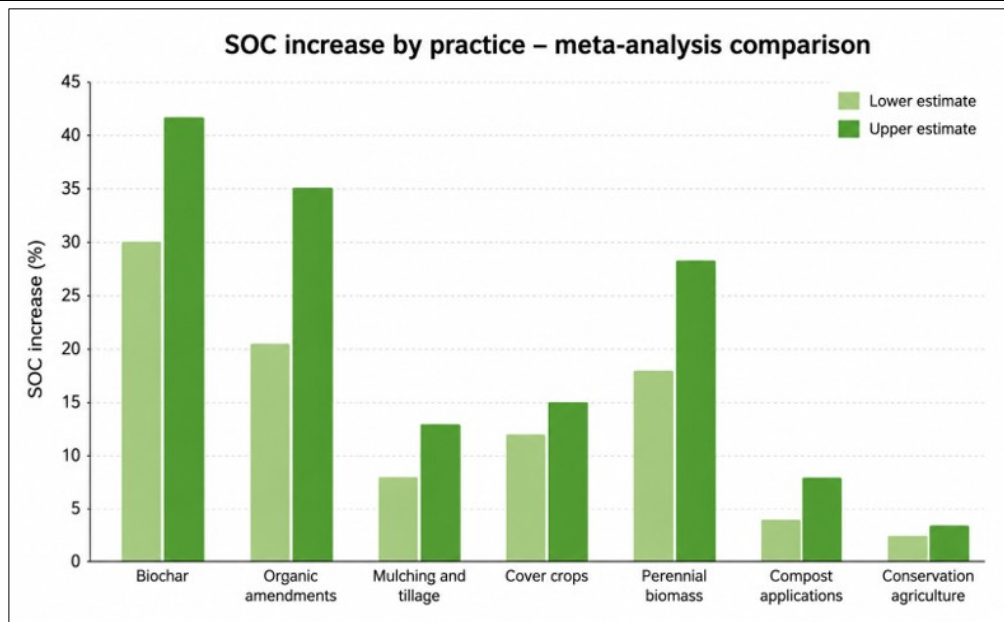


Fig. 8. Soil organic carbon (SOC) increase associated with different agricultural management practices: evidence from global meta-analyses.

Measurement and verification challenges

The current state of MRV for agricultural carbon markets in India reveals fundamental inadequacies. Soil carbon certificate schemes lack robust, long-term monitoring to ensure permanence, detect reversals and account for measurement error and model uncertainty (55). There is no widely accepted standard for SOC change metrics, error-bounded monitoring protocols, or models to estimate the duration and climate relevance of temporary removals. Large-scale incentive programmes for sustainable agriculture rarely collect high-resolution biophysical data, undermining accurate estimation of environmental services including carbon storage (30). Land degradation, itself a major driver of net GHG emissions and reduced carbon sink capacity, further complicates baseline setting for Indian agricultural carbon projects (42). The critical gap for India is the absence of a national, field-validated, high-resolution agricultural carbon inventory that can serve as the foundation for credible MRV infrastructure, supported by harmonised IPCC methodologies (32). Core challenges are high spatial/temporal SOC variability, absence of a standardised error-bounded monitoring protocol, high cost of repeated deep-soil sampling and lack of harmonised IPCC-aligned baselines for India.

Gaps in modelling and forecasting carbon market impacts

Existing carbon price modelling heavily emphasises forecasting accuracy but rarely links prices to real-economy outcomes such as technology adoption, land-use change, or agricultural mitigation performance (56, 57). Conventional integrated assessment models impose fixed technologies and behaviours, under-representing innovation, path-dependence and tipping

dynamics in low-carbon agricultural transitions (58). The multi-market and financial linkages of agricultural carbon markets also remain poorly specified; studies on green finance document complex spillovers among carbon markets, green bonds and renewable energy, but focus on financial returns rather than sector-specific mitigation or rural welfare outcomes (59, 60). Current models often rely on fixed assumptions about technology adoption, carbon prices and farmer behaviour and therefore may not adequately capture heterogeneous smallholder responses or transaction costs in Indian agriculture.

Lack of standardised co-benefit assessment approaches

Co-benefit research is dominated by air-quality and health domains; soil quality, biodiversity, water and energy security are comparatively sparse and rarely monetised (61). Climate policy assessments frequently omit co-benefits entirely, leading to biased decision-making that overweights mitigation costs. Existing agricultural sustainability frameworks are not standardised globally and are seldom integrated with carbon pricing or offset mechanisms (62). Large scoping reviews emphasise the lack of methods to trace causal pathways from carbon payments through adoption to environmental, productivity and equity outcomes (30). Evidence gap severity has been observed across six dimensions and depicted in Fig. 9. The list of research gaps and their priority actions is depicted as a research gap matrix in Table 5.

Future research should prioritise long-term field validation of MRV methods, India-specific carbon-market and farm-level models, transaction-cost studies, FPO-based aggregation models and evidence on equitable benefit sharing.

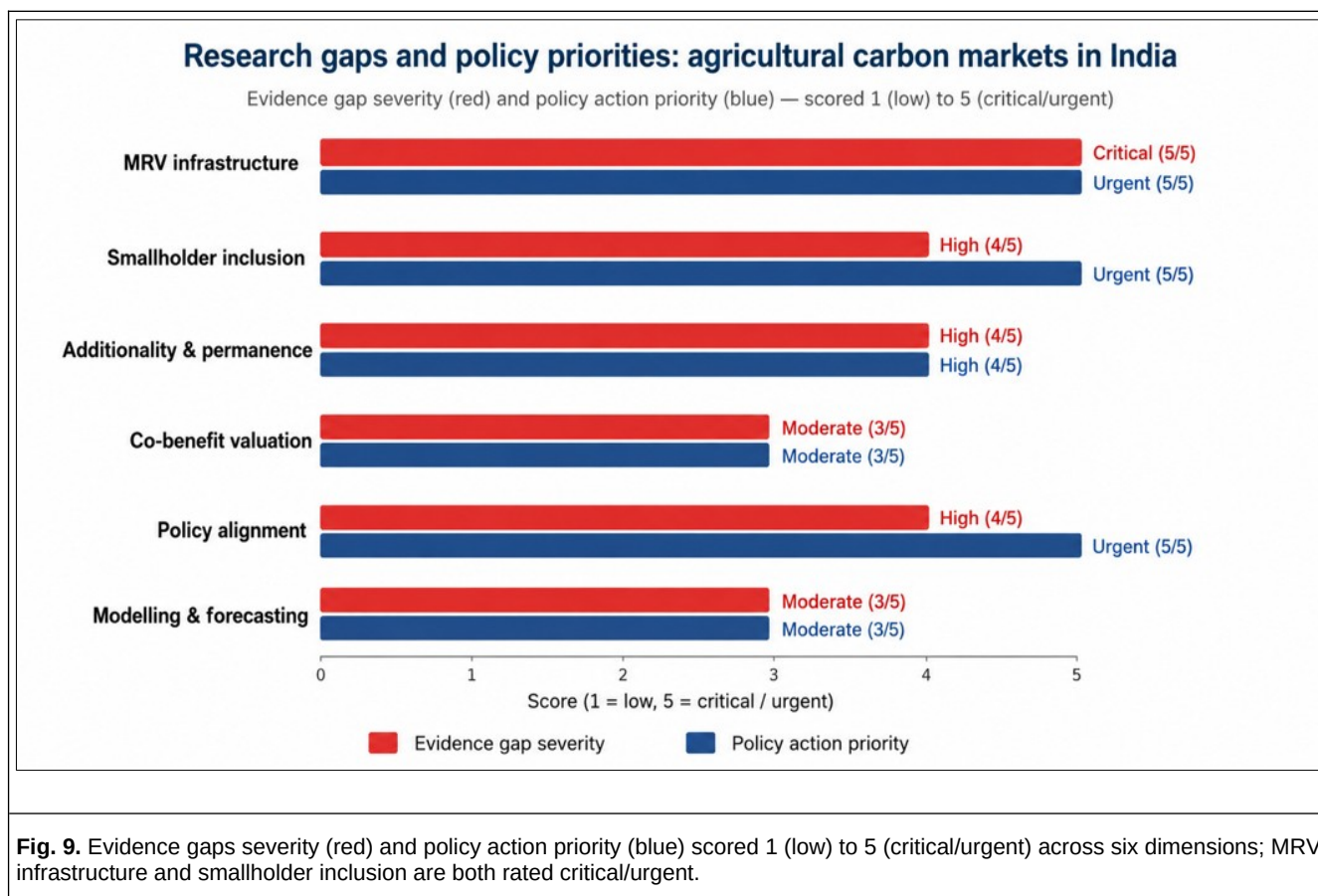


Table 5. Research gaps matrix for carbon markets in Indian agriculture

Gap area	Current limitation	Implication for carbon markets	Priority action
MRV infrastructure	Lack of field-validated, high-resolution carbon data	Risk of over-crediting or weak credibility	Develop national soil carbon and emissions monitoring systems
Additionality and permanence	Unclear baselines and risk of practice reversal	Credits may not represent durable mitigation	Use conservative baselines, long-term monitoring and buffer mechanisms
Smallholder inclusion	High transaction costs and uneven access to digital systems	Benefits may concentrate among larger or better-connected farmers	Support aggregation models, extension services and fair benefit-sharing
Co-benefit valuation	Soil health, biodiversity and water benefits are rarely monetised	Projects may undervalue broader sustainability gains	Develop standardised co-benefit indicators and reporting frameworks
Policy alignment	Carbon markets remain disconnected from agricultural support schemes	Fragmentation can reduce adoption and long-term impact	Align carbon finance with soil health, climate and rural development policies

Note: MRV: measurement, reporting and verification.

4. Conclusion

This systematic review shows that agricultural carbon markets in India have substantial mitigation potential but remain at an early stage of development. Alternate wetting and drying (AWD) and biochar currently offer stronger near-term market opportunities, while conservation agriculture, residue management, precision nutrient management and agroforestry require stronger measurement, reporting and verification (MRV), baseline data and evidence on additionality and permanence. Across practices, the credibility of carbon

credits depends on robust MRV, while high transaction costs, market volatility, leakage and limited smallholder participation remain important constraints. India has an opportunity to develop an agricultural carbon market that supports both climate mitigation and sustainable rural development. However, scaling should be guided by scientific credibility, transparent MRV, environmental integrity and equitable farmer participation rather than mitigation potential alone. Building these foundations will be essential for a credible, inclusive and durable agricultural carbon market in India.

India's nascent agricultural carbon market has growing voluntary carbon-farming activity but uneven participation due to barriers faced by smallholders, tenant farmers, women and marginalised groups. Limited domestic regulation, uncertain benefit-sharing, additionality and permanence also limit market confidence. Agronomic practices such as AWD, biochar, conservation agriculture, residue retention, precision nutrient management and agroforestry provide opportunities for reducing emissions, increasing soil carbon and improving soil fertility and resilience of farms. Alternate wetting and drying and biochar have stronger market potential in the near term, while bundles of integrated practices may be more effective for diverse smallholder systems. Rice methane, soil nitrous oxide, residue-burning emissions and soil-carbon changes all require different approaches to monitoring. Credible carbon markets require reliable baselines, field-level monitoring and robust MRV. Adequate safeguards must be in place to prevent over-crediting and exclusion of farmers. Finally, soil health should be central to carbon-market design. Although soil organic carbon sequestration improves fertility, water retention, nutrient cycling and productivity, its permanence depends on sustained management. Carbon-crediting programmes should therefore account for reversibility, saturation and local soil conditions while supporting practices that maintain long-term soil function.

Based on these findings, four policy priorities emerge. First, India needs a robust agricultural carbon MRV system, supported by field-validated soil carbon data, standardised monitoring protocols and transparent verification procedures. Second, carbon market methodologies should be tailored to Indian farming systems, with clear rules for additionality, permanence, leakage and long-term monitoring. Third, market design must actively include smallholders, women farmers, tenant farmers and marginalised farming communities through aggregation models, accessible digital tools, fair benefit sharing and extension support. Fourth, agricultural carbon markets should be aligned with existing agricultural, soil health, climate and rural development policies so that carbon finance strengthens, rather than replaces, broader sustainability goals.

Overall, the evidence indicates that agricultural carbon markets in India have considerable mitigation potential but remain constrained by uncertainty in measurement, reporting and verification (MRV) systems, permanence, additionality, transaction costs, market volatility and limited smallholder inclusion. India has a timely opportunity to develop a credible and inclusive agricultural carbon market architecture. Realising this opportunity will require moving beyond fragmented voluntary initiatives towards a system that combines sound science, clear regulation, farmer-centred design and long-term institutional support. If these conditions are met, carbon markets can become an important part of India's transition towards a more climate-resilient, low-carbon and sustainable agricultural future.

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Authors' contributions

SR conceived the review, conducted the literature search, screened and synthesised the literature, prepared the figures and tables and drafted the manuscript. KN guided the conceptualisation and organisation of the review, critically revised the manuscript and approved the final version of the manuscript. SSP contributed to the conceptual framework, critically reviewed the manuscript and provided overall supervision. MK assisted with the interpretation of the literature, reviewed the manuscript and provided valuable suggestions. SS was involved in the conceptualisation of the review, critically reviewed the manuscript and provided expert guidance. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors used AI-assisted language tools such as Grammarly and QuillBot solely for linguistic refinement and grammar improvement. All scientific interpretation, analysis and conclusions were independently developed, critically evaluated and verified by the authors.

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