

A REVIEW ON SOIL CARBON FUTURES: INDIAN RESEARCH PATHWAYS FOR SOIL HEALTH, CARBON SEQUESTRATION AND CLIMATE-RESILIENT LAND MANAGEMENT

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ABSTRACT

Soil carbon is a critical component of agricultural soil health, ecosystem functioning, climate regulation, and the long-term resilience of food production systems. In India, increasing climate variability, rising temperatures, droughts, floods, soil degradation, and declining soil organic matter pose significant challenges to sustainable agricultural production. This review examines the current status of soil carbon research in India and evaluates its potential contribution to climate-resilient agriculture. The review synthesizes evidence on major soil carbon pools, including soil organic carbon, particulate organic carbon, mineral-associated organic carbon, dissolved organic carbon, microbial biomass carbon, and aggregate-associated carbon, with emphasis on their formation, stabilization, persistence, and sensitivity to environmental and management factors. The distribution and dynamics of soil carbon across major Indian agro-ecological regions and soil types are discussed, along with the effects of conservation agriculture, crop diversification, residue retention, cover cropping, organic amendments, biochar, agroforestry, integrated nutrient management, and improved water management. Particular attention is given to the interactions among soil carbon, soil health, crop productivity, greenhouse-gas emissions, and resilience to drought, heat, and excess rainfall. Recent advances in soil-carbon measurement, spectroscopy, remote sensing, geographic information systems, machine learning, process-based modelling, and measurement, reporting and verification (MRV) systems are also reviewed. The analysis highlights major research gaps, including limited long-term field datasets, inadequate representation of deep-soil carbon, uncertainty in carbon permanence, insufficient integration of CO₂, CH₄ and NO₂ emissions, and limited region-specific evidence for smallholder farming systems. Finally, a research roadmap, termed “Soil Carbon Futures in India,” is proposed to integrate long-term experimentation, digital soil-carbon mapping, robust MRV frameworks, farmer-centred management, and supportive policy mechanisms. Strengthening soil-carbon research and its translation into region-specific management strategies can provide an important pathway for improving soil health, sustaining agricultural productivity, mitigating greenhouse-gas emissions, and enhancing the climate resilience of Indian agriculture.

KEYWORDS: Soil organic carbon; Carbon sequestration; Climate-resilient agriculture; Soil health; Greenhouse-gas emissions; Sustainable soil management; Carbon MRV; Indian agro-ecosystems

INTRODUCTION

Agriculture in India is increasingly challenged by climate variability, rising temperatures, changing precipitation patterns, recurrent droughts and floods, land degradation, and declining soil quality. These pressures pose significant risks to agricultural productivity, food security, rural livelihoods and the sustainability of natural resources. At the same time, the agricultural sector is closely connected with the global carbon cycle through the exchange and storage of carbon in soils, vegetation, livestock systems and agricultural inputs. Consequently, carbon management has emerged as an important component of strategies aimed at simultaneously improving soil health, reducing greenhouse-gas emissions and strengthening the resilience of agricultural production systems. An important emerging priority is the development of robust measurement, reporting and verification (MRV) systems for agricultural carbon. Reliable MRV is essential for distinguishing genuine and persistent changes in soil carbon from variations caused by sampling depth, seasonal conditions, analytical methods and spatial heterogeneity. Standardized field protocols, laboratory measurements, spectroscopy, remote sensing and model-based approaches can be integrated to develop cost-effective and scalable monitoring systems. Such systems are also important for evaluating climate-mitigation interventions, designing carbon incentives and ensuring transparency in emerging agricultural carbon markets. Integrating carbon science with climate-smart management, digital technologies, landscape-scale assessment and farmer-centred innovation can provide a foundation for resilient agricultural systems. This review therefore examines the major soil-carbon pools and

stabilization mechanisms, regional patterns of soil carbon, management practices for carbon sequestration, impacts on soil health and crop productivity, approaches for SOC measurement and MRV, and the major research priorities required to advance “Soil Carbon Futures in India” and climate-resilient agriculture.

As India faces heightened climate vulnerability, soil organic carbon sequestration has emerged as a cornerstone for both food security and climate change mitigation (Jat et al., 2022). Integrating soil carbon management into national strategies is increasingly critical to advancing climate-resilient agriculture, which seeks to stabilize productivity amidst fluctuating hydro-meteorological conditions (Sahoo et al., 2024). This review synthesizes current evidence on integrated nutrient management and microbial dynamics to evaluate how soil carbon stocks can be optimized within major cropping systems like rice-wheat (Padbhushan et al., 2021). By examining the intersection of long-term fertilization trials and emerging microbial ecology, this analysis identifies critical data gaps concerning the stability of carbon sequestration under intensive agricultural practices (Paramesh et al., 2023; Ranjan et al., 2023). Furthermore, this assessment evaluates the efficacy of residue management strategies and policy frameworks designed to incentivize sustainable land use among smallholder farmers (Buck & Palumbo-Compton, 2022; Korav et al., 2024). By systematically categorizing findings from long-term field experiments, we address the inherent trade-offs between yield intensification and soil organic carbon saturation potential (Moinet et al., 2023). This review further explores the microbially mediated mechanisms that facilitate carbon accrual under conservation agriculture, emphasizing the role of fungal succession and microbial growth efficiencies in sequestering carbon at decadal scales (Tian et al., 2024).

2. Soil Carbon Pools, Dynamics and Stabilization Mechanisms

2.1 Soil organic carbon (SOC) - is a dynamic component of the terrestrial carbon cycle and represents an important interface between agricultural productivity and climate regulation. Soil carbon occurs in several pools that differ in chemical composition, physical protection, turnover rate and susceptibility to decomposition. Understanding these pools is essential for assessing the potential of agricultural soils to sequester carbon and retain it over meaningful time scales. Broadly, soil carbon can be categorized into particulate organic carbon (POC), mineral-associated organic carbon (MAOC), dissolved organic carbon (DOC), microbial biomass carbon (MBC), aggregate-protected carbon and recalcitrant or passive carbon pools. In addition, inorganic carbon, particularly carbonates, can constitute an important carbon reservoir in many semi-arid and arid soils of India.

2.2 Soil inorganic carbon - Soil inorganic carbon (SIC), mainly occurring as calcium and magnesium carbonates, represents a substantial carbon reservoir in dryland and semi-arid environments. Large areas of India's drylands contain calcareous soils in which carbonate dynamics can influence total soil-carbon stocks. Carbonate formation, dissolution and redistribution are controlled by soil moisture, mineral composition, pH, irrigation, vegetation and carbon dioxide availability. Although inorganic-carbon dynamics differ fundamentally from biological SOC sequestration, they should be incorporated into comprehensive national soil-carbon assessments, particularly in regions where inorganic carbon represents a significant proportion of total soil carbon.

The active pool, which includes microbial biomass carbon and particulate organic matter, serves as a rapidly cycling nutrient reservoir and responds readily to inputs such as organic manure and crop residues (Angst et al., 2023; Zhao et al., 2023). The slow and passive pools turn over more gradually. Mineral-associated organic matter and other relatively persistent compounds contribute to these pools, supporting long-term soil structure and carbon storage (Bagwan et al., 2023; Ling et al., 2025). Interactions among the pools shape carbon fluxes: microbial activity transforms labile residues into forms that can become associated with soil minerals and persist longer (Villat & Nicholas, 2024). In Indian agroecosystems, management practices such as applying vermicompost or rice straw can affect carbon fractions differently, promoting the accumulation of more readily oxidizable or more persistent carbon (Ghosh et al., 2021). Soil macroaggregates can also physically protect organic matter from decomposition, helping carbon persist in the soil matrix (Audette et al., 2021). Regenerative practices, particularly no-till and cropping-system intensification, can increase both particulate and mineral-associated organic carbon, strengthening the soil's capacity to store carbon (Prairie et al., 2023). By reducing aggregate disruption, these practices may limit particulate organic carbon losses and influence microbial communities in ways that support long-term soil fertility (Zhang et al., 2023). However, aggregate occlusion does not guarantee permanence: aggregates may turn over within months, and a single fractionation measurement cannot show how long carbon has been physically protected (Poeplau et al., 2018). Accordingly, research has increasingly examined how fungal biomass influences microaggregate turnover and, in turn, the persistence of carbon within aggregates (Qiu et al., 2022). The passive pool consists of relatively persistent organic–mineral complexes that resist microbial decomposition over extended periods, making it an important contributor to soil carbon stocks (Kumar et al., 2022). Specifically, this mineral-associated organic matter relies on mechanisms such as chemical bonding to reactive surfaces and pore sorption to limit microbial accessibility, often resulting in turnover times significantly longer than those of particulate organic matter (Georgiou et al., 2022; Witzgall et al., 2021; Zhou et al., 2024).

2.3 Pools and Stabilization

Within the diverse agro-climatic zones of India, stabilization is primarily governed by the formation of organo-mineral complexes, where clay content and soil texture dictate the physical protection of carbon against oxidative enzymatic degradation.

Furthermore, spatial inaccessibility within microaggregates and intercalation within phyllosilicates significantly restrict microbial access to organic substrates, facilitating medium-term persistence (Song et al., 2022). Additionally, the synergistic interaction between organic inputs and native soil minerals promotes the development of stable aggregate structures, which serve as a critical defense against decomposition in intensively managed Indian soils (Angst et al., 2021; Kan et al., 2021). In black soils, the retention of cereal and legume residues further promotes these stabilization processes by providing the substrate necessary for humification and aggregate development (Kumawat et al., 2023). The persistence of these organo-mineral associations is essentially constrained by the surface area of fine-sized minerals, as further carbon stabilization becomes limited once these reactive sites reach saturation (Liang et al., 2023). Beyond these chemical controls, microbial necromass generated from the decomposition of crop residues serves as a vital precursor that, once stabilized via sorption onto these mineral surfaces, contributes significantly to long-term carbon storage (Chen et al., 2021; Mayer et al., 2023). Furthermore, the relative abundance of reactive mineral surfaces across varying Indian soil orders—ranging from the high-clay Vertisols to the more weathered, acidic soils of the Northeast—dictates the specific capacity for such organo-mineral associations to resist microbial recycling (Derrien et al., 2023; Reichenbach et al., 2021). In these environments, the inherent mineralogy, particularly the concentration of phyllosilicates and iron/aluminum oxides, creates a 'mineral filter' that selectively determines the chemical composition and long-term storage potential of the soil organic matter (Schweizer et al., 2021). However, the efficacy of these protective mechanisms in rice-based systems is frequently modulated by fluctuating redox conditions, which can destabilize iron-bound organic complexes and increase vulnerability to mineralization (Liu et al., 2021). Specifically, the reductive dissolution of iron oxides under waterlogged conditions can disrupt mineral-organic associations, thereby releasing previously protected carbon back into the soil solution (Kirsten et al., 2021; Xu & Tsang, 2024).

3. Distribution of Soil Carbon Across Indian Agro-Ecological Regions

India's substantial climatic, topographic and edaphic diversity produces marked spatial variation in soil-carbon stocks and turnover. Soil carbon is generally influenced by the interaction of temperature, precipitation, vegetation productivity, soil texture, mineralogy, drainage and land-use history. Consequently, carbon-management strategies developed for one agro-ecological region cannot necessarily be transferred directly to another region without considering local biophysical conditions.

In southwestern India, for instance, climate-driven gradients ranging from sub-humid to semi-arid regimes significantly modulate the storage capacity and quality of organic matter across varied geologies (Bellè et al., 2021). Conversely, in the Indo-Gangetic Plains, intensive rice-wheat rotation systems exert a dominant influence on carbon storage, where the combined application of synthetic fertilizers and organic residues has been shown to significantly enhance soil organic carbon sequestration (Xing et al., 2025). In these regions, however, the observed sequestration often shows vertical stratification, as agricultural inputs primarily influence topsoil carbon pools while leaving deeper layers less responsive (Liao et al., 2025). In contrast, the high-altitude regions of the Himalayas exhibit distinct carbon dynamics, where cold-limited decomposition processes often result in greater accumulation of particulate organic fractions compared to mineral-associated carbon observed in warmer lowland soils (Georgiou et al., 2024). Across the peninsular region, the prevalence of Vertisols provides a unique geochemical context where phyllosilicate minerals like smectite promote organo-mineral associations through cation bridging, leading to higher turnover times for subsoil carbon compared to less reactive soil types (Henneron et al., 2022). Conversely, semi-arid regions frequently experience significant SOC depletion, with losses ranging from 50% to 67% of original pools due to the synergistic stressors of intensive tillage and high-temperature oxidation (Gorooui et al., 2023). Moreover, research indicates that these carbon dynamics are significantly modulated by water management, as soils subjected to cyclic aerobic and anoxic conditions often maintain higher organic carbon stocks than continuously aerated upland soils (Liang et al., 2021; Liu et al., 2023). These regional disparities underscore that soil carbon sequestration capacity is not uniform, but is instead highly contingent upon the baseline storage levels and the inherent mineralogical susceptibility of specific pedological zones (Lal et al., 2021; Liu et al., 2024).

3.1 Evidence Across India

A comprehensive meta-analysis of over 1,786 paired datasets indicates that land-use conversion remains a primary driver of carbon loss, with grasslands exhibiting the most significant reduction in organic carbon stocks compared to native forest ecosystems (Padbhushan et al., 2022). Conversely, the transition to conservation agriculture—specifically the integration of organic amendments and cover cropping—has demonstrated a notable capacity to mitigate these losses, with partial substitution of mineral fertilizers by organic sources yielding up to a 34% increase in soil organic carbon in some cropland systems (Beillouin et al., 2023). These gains remain highly variable, however, as the meta-analytical evidence suggests that the efficacy of such practices is constrained by the limited geographical focus of long-term experimental trials in diverse agro-ecological zones (Beillouin et al., 2021). Global assessments have identified India as possessing one of the highest potential capacities for soil

organic carbon sequestration in its croplands (Herzfeld et al., 2021), highlighting an urgent need for more spatially explicit, field-scale data to validate these theoretical projections under local management regimes. Addressing this knowledge gap requires systematic, long-term monitoring of carbon saturation thresholds and microbial dynamics to move beyond current, often localized, experimental paradigms (Groß & Glaser, 2021). Future research should prioritize system-based evaluations, as the simultaneous implementation of multiple practices—such as combining residue retention with reduced tillage—often yields higher sequestration potential than the adoption of individual measures in isolation (Rosinger et al., 2022). Furthermore, while organic amendments such as compost and manure are recognized for enhancing soil organic carbon, their potential to simultaneously stimulate greenhouse gas emissions—particularly methane and nitrous oxide—necessitates a careful balancing of these trade-offs to ensure net climate mitigation (Tan & Kuebbing, 2023). Future efforts must also prioritize the subsoil profile, where deeper carbon sequestration potential remains poorly understood despite its capacity for long-term stabilization (Tiefenbacher et al., 2021). Integrating these findings into national agricultural policies requires moving beyond simplistic sequestration models toward a framework that accounts for the site-specific interactions between nutrient availability (Shi et al., 2024), tillage intensity (Meng et al., 2024), and regional climate regimes (Lessmann et al., 2021). Crucially, diversified cropping sequences that incorporate legumes such as black gram can improve nutrient cycling and microbial activity while supporting system productivity, offering a management option relevant to India's climate commitments (Babu et al., 2023). Long-term Indian field evidence likewise shows that pulse-inclusive rotations can increase SOC, microbial biomass, and soil enzyme activity, with associated gains in crop productivity, particularly when combined with integrated nutrient management (Borase et al., 2020). These benefits depend on the quantity and quality of biomass returned to the soil, however, underscoring the need to evaluate legume-based sequences under locally appropriate residue and nutrient-management practices (Bhardwaj et al., 2019).

4. Agricultural Management Practices for Soil-Carbon Sequestration

Conservation agriculture, Crop diversification and rotations. Cover crops, Crop-residue management, Organic amendments and compost, Biochar, Agroforestry, Integrated nutrient management, However, the long-term success of these conservation systems relies on the consistent application of permanent soil cover, as failure to integrate diverse crop residues or cover crops may negate potential carbon gains relative to conventional plowing (Sarker et al., 2022). Beyond surface management, the targeted promotion of pulse-based cropping systems represents a strategic frontier for deepening carbon pools through root biomass stabilization (Kumar et al., 2023). The increased root biomass and microbial activity characteristic of pulse-inclusive rotations enhance aggregate stability and soil moisture retention, providing a synergistic benefit to both crop resilience and long-term carbon storage. Furthermore, the transition to such diversified agroecosystems has been shown to enhance soil quality indices by up to two-fold, as improved aggregate stability bolsters nutrient cycling regardless of soil depth (Yan et al., 2023). By enhancing soil biogeochemical properties and moisture-holding capacity, these restorative practices ultimately buffer agricultural systems against the compounding stressors of climate change (Nath et al., 2023). Strategic integration of biochar and compost amendments further complements these conservation efforts by providing recalcitrant organic inputs that augment long-term soil carbon persistence while simultaneously reducing dependency on synthetic fertilizers (Ogle et al., 2023). In the Indo-Gangetic Plains, shifting from intensive rice-wheat rotations to maize-based systems with legume integration has demonstrated the potential to simultaneously enhance soil carbon stocks, stabilize agricultural yields, and address critical groundwater depletion (Nath et al., 2023; Pooniya et al., 2021). This transition emphasizes the importance of site-specific implementation, as the sequestration efficacy of these cropping systems is intrinsically linked to local climatic features and the quality of biomass returned to the soil (Siddique et al., 2023). Finally, while surface-level interventions are well-documented, investigating subsoil carbon stabilization mechanisms offers a promising, albeit under-researched, frontier for maximizing the total sequestration capacity of Indian agroecosystems (Button et al., 2022). Moreover, adopting intersectoral water management strategies alongside these soil practices is vital to mitigate erosion and preserve essential soil nutrients in the face of shifting climatic patterns (Filho et al., 2023). Adopting crop ideotypes engineered for enhanced root architecture and photosynthetic efficiency could further augment belowground carbon allocation, effectively transforming agricultural fields into durable sinks for climate mitigation (Jansson et al., 2021). These regenerative approaches necessitate a transition from conventional, high-input monocultures toward integrated systems that prioritize soil structure and biodiversity (Opa et al., 2025). Such transitions, aligned with regenerative agriculture principles, require the widespread adoption of minimal soil disturbance and year-round living roots to effectively rejuvenate degraded land and secure long-term agricultural productivity (Khangura et al., 2023). In tropical regions specifically, optimizing these strategies requires tailoring biochar application rates and organic inputs to soil-specific mineralogy to maximize recalcitrant carbon retention while mitigating potential greenhouse gas trade-offs (Adekiya et al., 2023).

5. Measurement, Monitoring, Modelling and MRV of Soil Carbon

Reliable measurement of SOC is fundamental to carbon research and the development of credible carbon-sequestration programmes. Conventional laboratory analysis provides accurate measurements but can be expensive and labour intensive when applied over large areas. Furthermore, spatial variability in soil properties means that inadequate sampling can introduce substantial uncertainty. Traditional SOC determination generally

involves laboratory analysis of soil samples collected at predefined depths. Sampling design should account for soil type, land use, management history, topography and spatial variability. Repeated sampling at the same locations is particularly important for detecting temporal changes. Soil spectroscopy, Remote sensing and geospatial technologies, Machine learning, Process-based modelling, MRV framework, Alternative SOC monitoring approaches: Domain a direct measurement and Domain b activity modelling. Standardizing this approach requires adopting empirical soil monitoring to depths of 60 cm to capture accurate SOC stock changes while mitigating the influence of spatial variability and bulk density shifts (Raffeld et al., 2024). These field-based measurements should subsequently be integrated into hybrid pipelines that utilize biogeochemical modeling to upscale local observations to regional levels, effectively accounting for practice-induced uncertainty and leakage (Bradford et al., 2023; Brummitt et al., 2024). Implementing such a framework necessitates the deployment of standardized biogeochemical models—such as Daycent or RothC—that can be calibrated with site-specific inputs, including initial SOC content and historical management data, to provide robust estimates of carbon sequestration potential (Keesstra et al., 2023). By integrating remote sensing data with these calibrated models, stakeholders can establish a robust MRV framework capable of generating verifiable, high-quality carbon credits for the Indian agricultural market (Baldassini et al., 2023; Fowler et al., 2023). To ensure long-term scalability, this digital-physical architecture should incorporate cloud-based data management systems that facilitate real-time monitoring and transparent verification of carbon stocks across diverse agro-climatic zones (Gelardi et al., 2023; Hammond et al., 2021). Furthermore, incorporating proximal sensing technologies such as mid-infrared spectroscopy alongside machine learning algorithms can significantly reduce the costs associated with dense grid sampling while maintaining high precision in SOC estimation (Li et al., 2023). This integrated strategy addresses current limitations in spatial resolution and data heterogeneity by leveraging standardized monitoring networks to validate model outputs across varying edaphic conditions (Bao et al., 2023). Moving beyond static inventories, this Tier 3 approach aligns with IPCC recommendations by prioritizing complex process-based simulations over simple emission factors, ensuring the methodological rigor required for high-integrity carbon credit generation (Garsia et al., 2023; Joensuu et al., 2021). However, achieving this level of accuracy requires rigorous standardization of soil processing methods, as the variability introduced during sample preparation is often overlooked in current quantification protocols. Consequently, establishing clear, uniform guidelines for soil handling is imperative to minimize analytical bias and ensure the reproducibility of carbon stock estimates across heterogeneous landscapes (Even et al., 2025). To reconcile the trade-offs between accuracy and cost, establishing a centralized benchmark dataset is essential for the independent validation of models against long-term, site-specific time-series data (Noë et al., 2023). Furthermore, adopting hybrid Bayesian frameworks for model calibration can effectively propagate parameter uncertainty, providing a statistically sound basis for quantifying carbon benefits (Mathers et al., 2023). Field-based spectroscopy, including visible and near-infrared and laser-induced breakdown spectroscopy, provides non-destructive, cost-efficient alternatives to labor-intensive laboratory assays (Loria et al., 2024). However, while these proximal sensing tools offer high-throughput potential, they necessitate robust calibration against comprehensive regional spectral libraries to maintain accuracy across diverse soil types (Helfenstein et al., 2021; Ramirez et al., 2021). Furthermore, integrating these spectral measurements with spatially explicit sampling protocols allows for the mitigation of small-scale soil variability, which often drives measurement uncertainty in heterogeneous landscapes (Baumann et al., 2021). Remote sensing further augments these field data by providing continuous environmental covariates that capture land-surface dynamics and historical biomass production, which are critical for constraining predictive biogeochemical models (Ali et al., 2025; Hashimoto et al., 2023). To refine the precision of these integrated forecasts, advanced machine learning architectures—such as Random Forest or Artificial Neural Network algorithms—can be employed for spectral band analysis to identify optimal inputs from these high-dimensional remote sensing datasets (Ammara et al., 2024). Moreover, combining these multi-source data streams through deep-learning frameworks allows for the simultaneous processing of temporal satellite indices and proximal soil data to minimize prediction errors to within 10% (Yüzügüllü et al., 2024; Zayani et al., 2023). Specifically, the transition toward multi-scale ensemble machine learning facilitates the ingestion of heterogeneous datasets, enabling the automated optimization of variable importance and covariate selection across expansive agricultural tracts (Hengl et al., 2021). Such models further benefit from the inclusion of 3D+T (three-dimensional space and time) covariates, which allow for the capture of soil organic matter dynamics without necessitating redundant measurements at fixed coordinates (Helfenstein et al., 2024). Furthermore, the efficacy of these predictive systems is significantly enhanced when mineral and organic soil matrices are modeled independently, accounting for their distinct carbon stabilization mechanisms (Sakhæe et al., 2022). Comparative studies suggest that while laboratory-based hyperspectral data often yield higher predictive precision due to reduced environmental noise, satellite imagery remains indispensable for scaling these insights across vast, topographically complex regions (Jin et al., 2024). To optimize this multi-scalar approach, research must prioritize the fusion of diverse satellite sensors to improve spatial resolution, while ensuring that the temporal windows for image acquisition are strictly constrained to peak vegetative cycles to minimize spectral noise (Luo et al., 2023). Moreover, implementing conformal prediction techniques within these workflows offers a rigorous mechanism for uncertainty quantification, ensuring that derived carbon stock estimates maintain statistical reliability for policy-oriented decision-making (Kakhani et al., 2024). To operationalize this integrated approach, a tiered Measurement, Reporting, and Verification framework should leverage proximal sensor networks for local ground-truth

calibration, while utilizing satellite-derived time-series data to provide the spatial coverage necessary for scaling predictions to regional agricultural landscapes (Vaudour et al., 2022; Wang et al., 2023). This hierarchical approach ensures that localized data-driven models, which excel in capturing fine-scale pedogenic variability, are systematically extrapolated using deep learning frameworks that leverage high-resolution earth observation data (Helfenstein et al., 2024; Odebiri et al., 2021). Crucially, such an MRV architecture must incorporate geostatistical methods—such as regression cokriging or spatial stochastic cosimulation—to account for spatial correlation in prediction errors, a step that pure machine learning approaches often fail to address (Sztatmári et al., 2021). Moreover, the operational success of this framework requires standardizing the separation of particulate organic matter and mineral-associated organic matter within these predictive pipelines, as their distinct stabilization pathways are sensitive to varying agricultural management intensities (Angst et al., 2023).

6. Monitoring Frameworks

To establish a robust monitoring framework, it is imperative to integrate periodic on-ground validation with continuous remote sensing surveillance to detect real-time changes in soil carbon storage across heterogeneous agricultural plots. Such a multi-tiered MRV system should incorporate standardized mechanistic modeling to provide essential insights into carbon stabilization fractions—such as pH and mineralogy—which are critical for evaluating the long-term impact of regenerative practices (Billings et al., 2021). This integration necessitates the adoption of a digital registry infrastructure that synchronizes decentralized field reports with satellite-derived trend analyses to ensure transparency in carbon crediting (Wadoux et al., 2023). By leveraging blockchain-based ledgers to store these immutable data streams, stakeholders can authenticate sequestration claims while simultaneously addressing the inherent challenges of spatial heterogeneity and sample measurement errors (Stanley et al., 2023). Furthermore, bridging these technological layers requires region-specific calibration to account for the unique socio-ecological contexts of Indian agriculture, as local management intensity and climate variability significantly influence the efficacy of SOC sequestration practices (Rumpel & Chabbi, 2021). Additionally, establishing decentralized feedback loops between smallholder farmers and automated monitoring systems will be essential for incentivizing the widespread adoption of restorative soil practices, which have demonstrated a potential 36% increase in soil organic carbon stocks across Indian agricultural systems (Jat et al., 2022). To ensure the long-term viability of these frameworks, it is essential to focus on animal integration methods and site-specific management strategies, which remain under-researched despite their demonstrated potential for enhancing sequestration in diverse agro-ecological zones (Villat & Nicholas, 2024). Furthermore, aligning these frameworks with national soil health programs could facilitate the creation of cost-effective carbon markets, providing farmers with the necessary financial incentives to adopt residue retention and diversified cropping systems (Bruni et al., 2021). Developing such an ecosystem requires the deployment of low-cost, handheld sensing technologies that empower extension agents to provide real-time performance feedback, thereby bridging the gap between national-level data aggregation and field-scale adaptive management (Drinkwater & Snapp, 2022). Ultimately, this hierarchical integration of ground-truth validation and predictive modeling can resolve existing knowledge gaps regarding the biophysical drivers of soil carbon stocks across diverse Indian watersheds (Bagwan et al., 2023). Establishing this integrative pathway requires a standardized monitoring, reporting, and verification pipeline that ingests heterogeneous field inputs to produce credible, scale-dependent estimates of net emissions reduction (Brummitt et al., 2024). Successful implementation of this infrastructure depends on reconciling experimental measurement constraints—such as high labor demands and long-term analytical costs—with the computational efficiencies offered by machine learning-based greenhouse gas flux simulations. Consequently, transitioning toward a hybrid architecture—where sparse, high-fidelity empirical measurements calibrate broad-scale predictive models—is essential for overcoming the labor-intensive barriers inherent in current experimental carbon accounting (Harsányi et al., 2024). This approach enables the systematic valuation of soil carbon accumulation, transforming restorative management practices into verifiable assets for voluntary carbon markets (Carsten et al., 2023; Georgiou et al., 2022).

7. Major Research Gaps and Future Research Priorities

Despite increasing interest in agricultural carbon, several major knowledge gaps constrain the development of robust national carbon strategies. First, long-term field experiments covering multiple Indian agro-ecological regions remain insufficient. Many studies report short-term changes in SOC, whereas climate mitigation requires evidence of persistence over decades. Second, greater attention is needed to SOC fractions and permanence. Total SOC measurements alone cannot determine whether newly accumulated carbon is readily decomposable or stabilized in persistent pools. Greater use of POC, MAOC, microbial-derived carbon and aggregate-associated carbon measurements would improve understanding of sequestration mechanisms. Third, deeper soil layers require greater attention. Carbon may move below conventional sampling depths through root inputs, dissolved organic carbon transport and bioturbation. Future studies should therefore consider deeper soil profiles where appropriate. Fourth, carbon and greenhouse-gas measurements should be integrated. Simultaneous measurement of SOC, methane, nitrous oxide and carbon dioxide would provide a more complete assessment of climate benefits. Fifth, India requires improved national SOC datasets. Harmonized databases combining historical observations, new field measurements, soil properties, climate information and remote sensing products could provide the foundation for high-resolution digital soil-carbon mapping. Sixth, research should move from

individual practices toward management packages. Combinations of residue retention, diversified rotations, optimized fertilization, reduced tillage, water management and agroforestry may produce different outcomes from individual interventions. Seventh, uncertainty needs to become a central component of carbon accounting. Every estimate of sequestration should ideally include confidence intervals or uncertainty ranges arising from sampling, analytical methods, model structure and spatial prediction. Finally, research should better connect biophysical carbon sequestration with farmer economics and policy. Technologies that produce measurable carbon gains but are financially unattractive or operationally difficult are unlikely to achieve widespread adoption.

8. Proposed Research Roadmap: “Soil Carbon Futures in India”

A national soil-carbon research programme could be organized around five interconnected phases.

Phase I — Baseline assessment

The first priority should be the development of harmonized baseline SOC inventories across India's major soil types, cropping systems and agro-ecological regions. Standardized sampling protocols and digital databases should be established to provide a reliable reference against which future changes can be assessed.

Phase II — Long-term experimentation

Long-duration experiments should evaluate conservation agriculture, residue management, diversified rotations, organic amendments, agroforestry, biochar, nutrient management and water-management strategies. Experiments should simultaneously measure SOC pools, soil health, crop productivity and greenhouse-gas emissions.

Phase III — Digital carbon intelligence

Field observations should be integrated with spectroscopy, remote sensing, digital soil mapping, machine learning and process-based models. This would enable high-resolution estimation of SOC stocks and changes while reducing the cost of repeated field surveys.

Phase IV — Carbon MRV and farmer-centred implementation

Standardized MRV protocols should be developed for agricultural carbon projects. Demonstration farms and farmer-participatory platforms can test the technical, economic and social feasibility of carbon-management practices under real-world conditions.

Phase V — Policy integration and scaling

The final phase should connect scientific evidence with national climate policy, agricultural programmes, soil-health initiatives and potential carbon markets. Regional carbon-management guidelines should be developed rather than applying uniform recommendations across India.

The overarching objective should be to establish a national framework in which soil carbon is treated simultaneously as a climate asset, a soil-health indicator and a foundation for agricultural resilience. Future research must prioritize bridging the gap between small-scale empirical trials and landscape-level predictive modeling to address the high degree of uncertainty regarding SOC sequestration potential across diverse agro-climatic zones.

Specifically, research must urgently address the carbon-nitrogen nexus, as current evidence regarding how residue retention influences both sequestration and trace gas emissions like N_2O remains significantly limited (Pan et al., 2022). Furthermore, interdisciplinary investigations should transition toward participatory on-farm research models that integrate social factors with biophysical soil measurements to understand the complex decision-making processes governing farmer adoption of sequestration techniques. By fostering synergies between soil microbiologists, data scientists, and agricultural economists, this research must also define the site-specific thresholds at which carbon saturation limits the efficacy of input-intensive sequestration strategies. Long-term chronosequence studies are needed to clarify how legacy land use and mineralogical variation shape mineral-associated organic matter accumulation and saturation in weathered tropical soils (Bellè et al., 2021; Reichenbach et al., 2023). Moreover, establishing a comprehensive roadmap necessitates the development of national soil carbon mapping initiatives that prioritize the identification of high-potential sequestration corridors, thereby aligning regional agronomic interventions with broader climate mitigation targets. Ultimately, these initiatives must converge into a national policy framework that incentivizes long-term soil stewardship through performance-based payments, effectively transitioning Indian agriculture from a carbon-depleting sector to a primary sink for atmospheric CO_2 . To achieve this transition, policymakers must implement robust monitoring, reporting, and verification protocols that account for the non-linear trajectories of soil carbon sequestration under climate-stressed regimes. Ultimately, these longitudinal strategies must prioritize the restoration of soil-mediated

ecosystem services to ensure that carbon-positive agriculture enhances both adaptive capacity and food security across vulnerable agrarian regions. Such systemic shifts necessitate the institutionalization of localized knowledge repositories that synthesize historical management data with real-time soil health analytics. Implementing these data-driven platforms requires a standardized national soil carbon inventory that harmonizes diverse sampling methodologies across varying agro-ecological zones. Furthermore, filling the existing data voids in regions like the Eastern Indo-Gangetic Plains requires systematic longitudinal assessments to quantify how long-term integrated nutrient management alters carbon stability within high-input cropping systems (Ranjan et al., 2023). Beyond these assessments, research should evaluate the impacts of warming on microbial metabolic rates, which may inadvertently accelerate the decomposition of particulate organic carbon and jeopardize net sequestration gains (Ling et al., 2025). To mitigate these risks, future investigations must prioritize the role of fungal succession and microbial growth efficiency in enhancing the persistence of microbially-derived carbon under warming scenarios (Tian et al., 2024). Addressing the permanence of these storage gains is equally critical, as the viability of carbon-positive outcomes depends on the continuous, decades-long application of regenerative practices (Bamière et al., 2022; Derrien et al., 2023). Crucially, these longitudinal studies must account for soil organic carbon saturation limits, which can significantly attenuate the projected mitigation capacity of agricultural soils over the coming century (Moinet et al., 2023). Addressing this challenge requires a strategic transition toward agroforestry and integrated production systems, which facilitate deeper carbon stabilization through complex root-soil-microbial interactions (Kumar et al., 2022; Paramesh et al., 2023).

9. CONCLUSION

Carbon research provides an important scientific foundation for developing climate-resilient agriculture in India. Soil carbon influences soil structure, nutrient cycling, water availability, microbial processes and ecosystem functioning while also contributing to climate mitigation. However, carbon sequestration is highly dependent on soil, climate, crop and management conditions and cannot be represented by a single universal practice or national sequestration factor.

Future agricultural carbon strategies should therefore emphasize region-specific management, long-term monitoring, stable carbon pools, whole-greenhouse-gas accounting and farmer-centred implementation. Integration of field experimentation with spectroscopy, remote sensing, artificial intelligence and process-based modelling offers considerable potential for developing scalable soil-carbon monitoring systems.

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