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An Agricultural Soil Carbon Credit Framework for Indian Smallholder Farmers: Integrating Low-Cost Measurement Technologies and Farmer-Centric Incentive Mechanisms

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Abstract — Indian agriculture faces the dual challenge of enhancing soil health while mitigating climate change. This research paper presents a comprehensive agricultural soil carbon credit framework specifically designed for Indian smallholder farmers operating under semi-arid conditions. The framework integrates six core research objectives: (1) developing a reliable measurement and verification system suited to Indian farming conditions, (2) creating income opportunities through carbon credit programs, (3) establishing baseline data on soil organic carbon and health indicators, (4) implementing and evaluating soil management practices, (5) measuring seasonal and long-term changes in soil organic carbon, and (6) developing practical monitoring guidelines. The framework was developed using a doctrinal and conceptual research methodology based on a critical review and synthesis of existing literature, policy documents, carbon market mechanisms, and emerging soil carbon measurement technologies relevant to Indian agriculture. We propose innovative solutions, including affordable low-cost measurement technologies (portable NIR spectroscopy, handheld sensors, smartphone-based tools), a Small Local Carbon Service Organisation (SLCSO) model for accessible carbon measurement services, green incentives with fast remuneration mechanisms featuring tiered payment systems, and a "Carbon Check First" mechanism providing free or subsidised initial baseline assessments. This framework addresses critical barriers preventing smallholder farmer participation in carbon markets, including high measurement costs, complex procedures, and delayed payments. By combining technological innovation with farmer-centric service delivery models, this research aims to transform Indian smallholder agriculture into a viable carbon-sequestration sector while improving farmers' livelihoods and soil health.

Keywords— Soil Carbon Sequestration, Carbon Credit Markets, Smallholder Farmers, Sustainable Agriculture, Low-Cost Soil Measurement Technologies, Carbon Farming Framework.

I. INTRODUCTION

India's agricultural sector, dominated by smallholder farmers cultivating fragmented landholdings, faces unprecedented challenges from climate change, soil degradation, and economic vulnerability. Agricultural soils in India are severely depleted in soil organic carbon (SOC), with concentrations often below 1 g kg^{-1} or barely 10-15 Mg C ha^{-1} at a depth of 40 cm (Lal, 2015). This depletion results from decades of extractive farming practices, threatening both food security and farmer livelihoods. Simultaneously, India's agriculture sector presents significant potential for climate change mitigation through soil carbon sequestration, with the capacity to reduce annual emissions by 84% from 2019 to 2070 through sustainable farming practices (Khurana et al., 2024).

Carbon farming, the practice of managing agricultural lands to sequester atmospheric carbon dioxide in soils and biomass, offers a promising dual solution: enhancing soil health while creating new income streams for farmers through carbon credit markets (Sharma et al., 2024). The global carbon credit market is projected to reach $97.1 billion by 2033, presenting substantial opportunities for Indian agriculture. However, existing carbon credit projects in India reveal systematic exclusion of small and marginalised farmers, with approximately 99% of participating farmers receiving no monetary benefit (Krishna et al., 2024). This exclusion stems from multiple barriers: prohibitively expensive soil testing procedures, complex verification requirements, high transaction costs, delayed payments, and a lack of accessible measurement infrastructure.

Current carbon credit frameworks fail to address the unique constraints of Indian smallholder farmers, who typically operate on landholdings of less than 2 hectares under resource-constrained conditions. Traditional soil carbon measurement relies on laboratory-based methods involving soil sampling, transportation, and dry combustion analysis, which are time-consuming, labour-intensive, and costly, often exceeding €44 per sample (Kohl et al., 2025). These costs create insurmountable barriers for smallholder farmers seeking to participate in carbon markets. Furthermore, the convoluted and unpredictable nature of receiving offset credits discourages farmer participation (Barbato et al., 2023).

This research paper addresses these critical gaps by developing an integrated agricultural soil carbon credit framework specifically tailored to Indian smallholder farmers. Our framework combines technological innovation in low-cost measurement equipment, institutional innovation through locally run service organisations, and financial innovation via simplified incentive mechanisms. By proposing and testing mechanisms to help farmers first conduct carbon baseline assessments and then proceed with the full carbon credit process, this research aims to democratise access to carbon markets and transform Indian smallholder agriculture into a viable carbon-sequestration sector.

Research Objectives

This study is guided by six interrelated objectives that address the technical, institutional, and economic barriers to smallholder participation in carbon credit programmes in India. It develops a context-specific soil carbon credit framework for semi-arid farming systems, integrating affordable measurement technologies, simplified verification procedures, and accessible service delivery models. The study further examines the potential for enhancing farmer income through carbon sequestration practices, with evidence suggesting that agroforestry-based carbon finance can increase income by 40–50%, potentially generating up to Rs. 25,000 per hectare annually (Singh et al., 2024), while also considering mechanisms for equitable benefit distribution. It establishes baseline data on soil organic carbon, bulk density, and key soil health indicators to ensure accurate measurement and additionality, a critical requirement for carbon credit eligibility (Cariappa et al., 2024).

In addition, it assesses the effectiveness of sustainable soil management practices, such as crop residue retention and organic amendments, which have demonstrated the potential to increase soil organic carbon stocks by up to 36% in the topsoil layer (Jat et al., 2022). The study also analyses seasonal and long-term variations in soil organic carbon to support reliable monitoring and verification, recognising that continuous monitoring is essential for ensuring permanence and measurement accuracy (Maho, 2023). Finally, it proposes simplified, farmer-friendly monitoring guidelines that balance scientific rigour with practical accessibility, addressing the complexity of existing systems that often limit smallholder participation (Krishna et al., 2024).

II. PROPOSED FRAMEWORK

Our proposed agricultural soil carbon credit framework integrates four key components: (1) accessible measurement infrastructure, (2) simplified verification procedures, (3) farmer-centric service delivery, and (4) streamlined payment mechanisms. This framework is designed to overcome the systematic barriers that currently exclude smallholder farmers from carbon markets. The framework begins with the "Carbon Check First" mechanism, which provides farmers with free or subsidised initial baseline assessments to eliminate upfront financial barriers. Following baseline establishment, farmers receive guidance on implementing carbon-positive practices, including conservation agriculture, crop residue retention, compost application, and integrated nutrient management. These practices have been demonstrated to enhance soil organic carbon while improving soil health indicators, including water retention, nutrient cycling, and microbial diversity (Sharma et al., 2024).

Measurement and verification are conducted using low-cost portable technologies operated by Small Local Carbon Service Organisations (SLCSOs), eliminating the need for expensive laboratory analysis. The framework employs a hybrid approach combining direct soil measurements with modelling, similar to the Soil Enrichment Protocol, which has demonstrated effectiveness in reducing data collection burdens while maintaining scientific rigour (Hammond et al., 2021). Field-level baselines and dynamic modelling enable accurate carbon stock estimation with as few as 0.5 samples per hectare (Maho, 2023). The verification process is simplified through tiered payment systems that provide quick initial payments based on practice adoption, followed by payments based on verified carbon sequestration.

This hybrid payment approach addresses the challenge of delayed remuneration while maintaining additionality requirements (Raina et al., 2024). Local monitoring organisations aggregate farmer contributions, reducing transaction costs that can range from 3% to 85% of total credit value (OECD, 2023). The framework emphasises inclusivity through differential pricing mechanisms that incentivise participation of small and marginalised farmers (Krishna et al., 2024). By addressing technical, economic, and institutional barriers simultaneously, this integrated framework creates a viable pathway for smallholder farmers to participate in carbon markets while improving soil health and farm productivity.

III. PROPOSED TECHNOLOGIES AND EQUIPMENT

The success of our framework depends critically on affordable, accurate, and farmer-accessible measurement technologies. We propose a suite of low-cost technologies that replace expensive traditional laboratory methods while maintaining sufficient accuracy for carbon credit verification.

1. Portable Near-Infrared (NIR) Spectroscopy

Portable NIR spectroscopy represents the most promising technology for field-based soil carbon measurement. Handheld NIR devices operating in the 350-2500 nm wavelength range can predict soil organic carbon with good accuracy ($R^2 = 0.85$, RMSE = 0.47) under field conditions, comparable to laboratory methods (England et al., 2018). The visible-near-infrared portable (vis-NIRp) spectrometer has been identified as the most cost-effective option for SOC estimation of ≤2 mm samples due to its low cost, high accuracy, and large measurement capacity (Li et al., n.d.). These devices are significantly cheaper than traditional laboratory analysis, with measurement costs of approximately €3-4 per sample compared to €44 for laboratory analysis (Kohl et al., 2025). Recent advances have produced increasingly affordable NIR spectrometers. The NanoQuest FT-NIR spectrometer, a compact and lightweight alternative to bulky research-grade instruments, demonstrates satisfactory SOC estimation (R^2: 0.17 to 0.70, RMSE: 5 to 9.2 g C kg^{-1}) at variable moisture contents (Murad et al., 2023). Portable vis-NIR spectrometers can cost less than AUD 10,000 to over AUD 100,000, with costs continually decreasing as smaller micro-electromechanical systems (MEMS) spectrometers emerge (England et al., 2018).

2. Handheld Sensors and Multi-Parameter Probes

Multi-sensor approaches offer a comprehensive soil health assessment beyond carbon measurement. The Stenon FarmLab multi-sensor probe provides portable, in-field SOC monitoring at approximately €3-4 per measurement, facilitating dense spatial sampling (Kohl et al., 2025). Novel sensor-in-field probes for real-time monitoring of soil health indicators, including total soil carbon, have demonstrated coefficients of variation below 20% and accuracy comparable to traditional laboratory analysis (Dhamu et al., 2025). Self-developed sensor systems based on simultaneous reflectance measurements at 660 and 940 nm wavelengths offer even lower running costs. These systems, incorporating built-in GPS units for mapping, make soil carbon research "much cheaper and faster" than laboratory tests, with strong correlations ($R^2 = 0.73$) between sensor values and reference measurements (Béni et al., 2021).

3. Smartphone-Based Tools and Colour Sensors

Smartphone-based technologies represent the most accessible and affordable option for smallholder farmers. The Nix Pro™ colour sensor, priced at $349, serves as a low-cost alternative to traditional colourimeters for soil organic carbon determination (Stiglitz, 2017). Controlled via Bluetooth and a mobile application, this device provides rapid and reliable colour analysis using linear regression models, achieving an R^2 of 0.7978 for dry soils. The accompanying Soil Scanner app enables GPS location recording, photo capture, and crowd-sourcing of soil data. Emerging technologies leverage Wi-Fi and optical signals for cost-effective soil carbon sensing. The Scarf system uses Wi-Fi signals to detect carbon content without dedicated hardware, achieving accuracy comparable to state-of-the-art techniques costing thousands of dollars (Ding et al., 2024). Prototype handheld devices that integrate measurements of soil colour, texture, moisture, bulk density, and NIR reflectance, with cloud storage via Wi-Fi, offer integrated, data-driven approaches to overcome the expense of traditional techniques (Acharya et al., 2022).

4. Laser-Induced Breakdown Spectroscopy (LIBS)

For higher-throughput applications, laser-induced breakdown spectroscopy offers a scalable solution. The commercially available LaserAg-Quantum analyser achieves an average limit of quantification of 0.75% carbon with 4.10% precision, providing a robust alternative to time-consuming, energy-intensive traditional methods (Morais et al., 2024).

5. Technology Selection Criteria

For the proposed framework, we recommend a tiered technology approach: (1) smartphone-based color sensors for initial screening and farmer self-monitoring (cost: $300-400), (2) portable NIR spectrometers for SLCSO-operated baseline and verification measurements (cost: $5,000-15,000), and (3) multi-sensor probes for comprehensive soil health assessment in research and validation contexts (cost: $10,000-30,000). This tiered approach balances affordability, accuracy, and accessibility while maintaining scientific rigour for carbon credit verification.

6. Small Local Carbon Service Organisation (SLCSO)

The Small Local Carbon Service Organisation (SLCSO) model represents a critical institutional innovation that bridges the gap between smallholder farmers and carbon credit markets. SLCSOs are community-based organisations that provide affordable, accessible carbon measurement and verification services at the local level, addressing the infrastructure and expertise barriers that currently exclude smallholder farmers from carbon programs.

7. Organisational Structure and Functions

SLCSOs operate as locally-run entities staffed by trained technicians from farming communities who understand local agricultural practices, languages, and socio-economic contexts. Each SLCSO serves a cluster of villages or a defined geographic area, typically covering 500-1000 smallholder farmers. Core functions include: (1) conducting initial "Carbon Check First" baseline assessments, (2) providing technical guidance on carbon-positive farming practices, (3) performing periodic soil carbon monitoring using portable equipment, (4) maintaining farmer records and documentation, (5) aggregating farmer data for carbon credit verification, and (6) facilitating communication between farmers and carbon credit buyers. The SLCSO model draws on successful precedents set by intermediary organisations in agricultural carbon finance. Research demonstrates that intermediaries at the meso-level, including external agencies and local units such as farmer groups, effectively influence and incentivise production decisions while bridging micro-level farmers with macro-level buyers (Clements et al., 2015). Third-party intermediaries can aggregate contracts and reduce transaction costs, particularly for small farms (Antle et al., 2003).

8. Equipment and Capacity Building

Each SLCSO is equipped with portable NIR spectrometers, handheld multi-sensor probes, GPS-enabled tablets for data recording, and soil sampling equipment. Initial capital investment for equipment ranges from $15,000 to $ 25,000 per SLCSO and can be subsidised through government programs, corporate social responsibility funds, or carbon credit advance payments. SLCSO technicians receive comprehensive training in soil sampling protocols, equipment operation, data management, and farmer communication. Training programs developed in partnership with agricultural universities and research institutions emphasise practical skills and local-language instruction.

9. Service Delivery Model

SLCSOs operate on a fee-for-service model with subsidised rates for smallholder farmers. The "Carbon Check First" baseline assessment is provided free or at minimal cost (Rs. 50-100 per farmer) to eliminate entry barriers. Subsequent monitoring visits are charged at affordable rates (Rs. 200-500 per visit), significantly lower than commercial laboratory costs. Revenue is generated through: (1) farmer service fees, (2) commissions from carbon credit sales (typically 5-10% of credit value), (3) government subsidies for soil health monitoring, and (4) corporate sponsorships.

10. Community Engagement and Trust

Trust is a critical factor in farmer participation in carbon credit projects (Mallappa et al., n.d.). SLCSOs build trust through: (1) local staffing with community members, (2) transparent payment tracking and reporting, (3) regular farmer meetings and training sessions, (4) demonstration plots showcasing carbon-positive practices, and (5) farmer-to-farmer knowledge exchange. Community engagement in monitoring can significantly reduce project costs while increasing farmer ownership (Okoli et al., 2024).

11. Aggregation and Transaction Cost Reduction

A key function of SLCSOs is aggregating contributions from multiple smallholder farmers to achieve economies of scale. Individual smallholder farms typically sequester small amounts of carbon, making direct participation in carbon markets economically unviable due to high transaction costs. By aggregating 500-1000 farmers, SLCSOs create carbon credit volumes sufficient to attract buyers while distributing transaction costs across many participants. This aggregation model has proven effective in reducing per-farmer costs from prohibitive levels to manageable amounts (Antle et al., 2003).

12. Integration with Existing Institutions

SLCSOs are designed to integrate with existing agricultural institutions, including farmer-producer organisations (FPOs), self-help groups (SHGs), Krishi Vigyan Kendras (KVKs), and agricultural extension services. This integration leverages existing social capital, infrastructure, and farmer networks while avoiding duplication of services. Policy tools should offer targeted incentives, such as equipment subsidies and training through SHGs, to support the establishment of SLCSOs (Patil et al., 2025).

IV. GREEN INCENTIVES AND FAST REMUNERATION

Current carbon credit payment systems suffer from complexity, delays, and unpredictability that discourage smallholder farmer participation. Farmers express concerns about the convoluted and burdensome nature of receiving offset credits, with payments often delayed by years (Barbato et al., 2023). Our framework proposes innovative "green incentives" and "fast remuneration" mechanisms to simplify procedures and accelerate payments.

1. Tiered Payment System

We propose a three-tier payment structure that provides progressive remuneration aligned with farmer actions and verified outcomes:

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Tier 1: Practice Adoption Payments (Action-Based)
Farmers receive quick initial payments (Rs. 2,000-5,000 per hectare) upon verified adoption of carbon-positive practices such as zero tillage, crop residue retention, or compost application. These action-based payments are simpler to administer, require lower monitoring intensity, and can be paid upfront or shortly after practice implementation (Raina et al., 2024). This tier addresses immediate farmer cash flow needs and provides confidence-building early returns.

Tier 2: Interim Verification Payments (Hybrid)
After 6-12 months of practice implementation, farmers receive interim payments (Rs. 3,000-8,000 per hectare) based on preliminary soil carbon measurements and modelling estimates. This hybrid approach combines low-risk guaranteed payments with early result-based incentives, reducing farmer uncertainty while maintaining carbon sequestration verification (Raina et al., 2024).

Tier 3: Full Carbon Credit Payments (Result-Based)
Upon complete verification of carbon sequestration after 2-3 years, farmers receive full carbon credit payments based on verified carbon stocks. At current market rates of Rs. 780-2,000 per carbon credit, with potential for higher prices from corporate buyers (Singh et al., n.d.), farmers can earn Rs. 8,000-15,000 per hectare depending on sequestration rates and market conditions.

2. Carbon Loan Program
To address capital market imperfections and payment delays, we propose a "carbon loan" program that finances upfront investments by paying the capitalised value of expected carbon credits in advance (Antle et al., 2003). Farmers receive advance payments (50-70% of the projected carbon credit value) to invest in necessary inputs such as compost, cover crop seeds, or equipment. These advances are reconciled against the actual carbon credits generated, with any surplus returned to farmers and any deficits carried forward. This mechanism addresses the critical constraint that farmers often lack the capital to implement carbon-positive practices while waiting years for carbon credit payments.

3. Simplified Verification Procedures
Traditional carbon credit verification involves complex monitoring, reporting, and verification (MRV) processes that are time-consuming and costly. Our framework simplifies verification through: (1) standardised protocols for common practices (zero tillage, residue retention, compost application), (2) remote sensing integration to reduce field visits, (3) risk-based sampling where high-performing farmers receive less frequent monitoring, and (4) group verification where clusters of farmers implementing similar practices are verified collectively rather than individually.

4. Digital Payment Infrastructure
Fast remuneration requires an efficient payment infrastructure. We propose leveraging India's digital payment systems (UPI, Aadhaar-linked bank accounts) to enable direct, transparent, and rapid payments to farmers. SLCSOs maintain digital records of farmer participation, practice adoption, and carbon measurements, enabling automated payment triggers when verification milestones are achieved. Blockchain-based systems can provide transparent tracking of carbon credits from generation to sale, building farmer trust through payment transparency (Mallappa et al., n.d.).

5. Differential Pricing for Inclusivity
To ensure small and marginalised farmers benefit equitably, we propose differential pricing mechanisms that give smaller landholdings premium rates per unit of carbon sequestered. This addresses the systematic exclusion observed in existing projects where 99% of farmers receive no monetary benefit (Krishna et al., 2024). Premium pricing (20-30% above standard rates) for farmers with less than 1-hectare landholdings compensates for higher per-hectare transaction costs while incentivising inclusive participation.

6. Corporate and Government Co-Financing
Green incentives can be enhanced through corporate social responsibility (CSR) funds and government subsidies. Corporations can support carbon credits through CSR funds, paying market prices as incentives (Singh et al., 2024). Government programs such as the Soil Health Card scheme, Pradhan Mantri Krishi Sinchayee Yojana, and National Mission for Sustainable Agriculture can integrate carbon credit support, providing co-financing for practice adoption payments and SLCSO infrastructure.

V. CARBON CHECK FIRST MECHANISM

The "Carbon Check First" mechanism represents a paradigm shift in how farmers engage with carbon credit programs. Rather than requiring farmers to commit to complex, long-term contracts before understanding their baseline carbon status, this mechanism provides free or heavily subsidised initial carbon baseline assessments, eliminating upfront financial and informational barriers.

1. Rationale and Design
Current carbon credit programs require farmers to invest time, money, and effort before knowing whether their soils have carbon sequestration potential or whether participation will be

economically viable. This uncertainty deters risk-averse smallholder farmers. The Carbon Check First mechanism reverses this sequence: farmers first receive a comprehensive baseline assessment of their soil carbon status, sequestration potential, and projected income from carbon credits, enabling informed decision-making before committing to the program. The mechanism operates through SLCSOs, which conduct initial baseline assessments covering: (1) soil organic carbon concentration and stocks (0-30 cm depth), (2) bulk density, (3) key soil health indicators (pH, available nitrogen, phosphorus, potassium), (4) soil texture and moisture, and (5) current management practices. These assessments utilise portable NIR spectroscopy and handheld sensors, providing results within 24-48 hours rather than the weeks required for laboratory analysis.

2. Subsidy Structure

The Carbon Check First assessment is provided free to farmers with landholdings of less than 2 hectares, subsidised at 75% for farmers with 2-5 hectares, and at market rates for farmers with 5+ hectares. Subsidies are funded through: (1) government soil health monitoring programs, (2) carbon credit advance payments from buyers, (3) corporate CSR funds, and (4) international climate finance mechanisms. The cost per baseline assessment is approximately Rs. 500-800 per farmer using portable technologies, making universal coverage economically feasible.

3. Farmer Decision Support

Following the baseline assessment, farmers receive a personalized report in local language detailing: (1) current soil carbon status compared to regional averages, (2) estimated carbon sequestration potential based on soil type and climate, (3) recommended carbon-positive practices suited to their farming system, (4) projected income from carbon credits over 3-5 years under different scenarios, (5) required investments and practice changes, and (6) comparison of carbon credit income with alternative income sources. This decision support empowers farmers to make informed choices about participation. Research indicates that farmers implement practices primarily for business and sustainability reasons, with carbon payments seen as "gravy on top" (Barbato et al., 2023). By clearly demonstrating both soil health benefits and income potential, the Carbon Check First mechanism aligns carbon credit participation with farmers' existing motivations.

4. Baseline Database Development

The Carbon Check First mechanism simultaneously addresses Research Objective 3 by establishing a comprehensive baseline database of soil organic carbon and health indicators across semi-arid farming systems. This database serves multiple purposes: (1) regional benchmarking for carbon credit additionality verification, (2) identification of high-potential areas for targeted interventions, (3) research on soil carbon dynamics under diverse management systems, and (4) policy development for soil health programs. Baseline data collection follows standardised protocols, ensuring comparability across regions and time periods. Soil samples are collected at 0-15 cm and 15-30 cm depths using systematic sampling designs. GPS coordinates, land use history, current management practices, and farmer socio-economic data are recorded. This comprehensive baseline enables accurate measurement of carbon stock changes and ensures additionality, a critical requirement for carbon credit eligibility (Cariappa et al., 2024).

5. Transition to Full Program

Farmers who choose to proceed after the Carbon Check First assessment transition seamlessly to the full carbon credit program. They receive: (1) technical training on recommended practices, (2) access to inputs and equipment through SLCSOs or farmer cooperatives, (3) Tier 1 practice adoption payments upon implementation, (4) ongoing monitoring and support from SLCSO technicians, and (5) entry into the tiered payment system. This smooth transition reduces friction and maintains farmer engagement.

6. Scalability and Replication

The Carbon Check First mechanism is designed for rapid scalability. Each SLCSO can conduct 10-15 baseline assessments per day using portable equipment, covering 500-1000 farmers within 2-3 months. The mechanism can be replicated across diverse agro-ecological zones with minimal adaptation, requiring only regional calibration of measurement equipment and adjustments to practice recommendations based on local conditions. Successful implementation in pilot regions can demonstrate viability and attract additional funding for expansion.

VI. DISCUSSION

This research paper presents an integrated framework to address the multifaceted barriers that prevent Indian smallholder farmers from participating in carbon credit markets. By combining technological innovation (low-cost measurement equipment), institutional innovation (SLCSOs), and financial innovation (tiered payments and Carbon Check First), the framework creates a viable pathway to transform Indian agriculture into a carbon-sequestration sector while improving farmer livelihoods and soil health.

1. Addressing Systematic Exclusion

Current carbon credit projects in India systematically exclude small and marginalised farmers, with 99% receiving no monetary benefit (Krishna et al., 2024). Our framework directly addresses this exclusion through: (1) eliminating upfront costs via Carbon Check First, (2) reducing measurement costs by 90% through portable technologies, (3) aggregating farmers through SLCSOs to achieve economies of scale, (4) providing quick initial payments to address cash flow constraints, and (5) implementing differential pricing to incentivize inclusive participation. These mechanisms collectively remove the financial, technical, and institutional barriers that currently prevent smallholder farmers from participating.

2. Balancing Rigour and Accessibility

A critical challenge is maintaining scientific rigour for carbon credit verification while ensuring accessibility for resource-constrained farmers. Our framework achieves this balance through: (1) validated portable measurement technologies with accuracy comparable to laboratory methods (England et al., 2018), (2) hybrid measurement-modeling approaches that reduce sampling intensity while maintaining precision (Maho, 2023), (3) standardized protocols for common practices that simplify verification, and (4) risk-based monitoring that focuses resources on verification-critical aspects. Research demonstrates that the precision of farm carbon stocks below 5% is achievable with as few as 0.5 samples per hectare using appropriate methods (Maho, 2023).

3. Additionality and Permanence

Carbon credit programs must demonstrate additionality (carbon sequestration would not have occurred without the program) and permanence (sequestered carbon remains stored long-term). Our framework addresses additionality through comprehensive baseline data establishing pre-intervention carbon stocks and regional adoption rates of carbon-positive practices. Eligibility criteria similar to those proposed by Cariappa et al. (2024), baseline adoption rates below 20%, no yield decreases exceeding 5%, and fertiliser reductions exceeding 5% ensure additionality. Permanence is addressed through: (1) long-term monitoring protocols, (2) farmer education on practice maintenance, (3) economic incentives for continued practice adoption, and (4) insurance mechanisms to address disadoption risks. The high disadoption rate (28%) observed in existing projects (Krishna et al., 2024) highlights the importance of ongoing support and incentives.

4. Soil Health Co-Benefits

Beyond carbon sequestration, the proposed practices deliver substantial co-benefits for soil health. Conservation agriculture practices enhance soil physical, chemical, and biological properties, boosting natural resource availability and nutrient cycling (Mrudula et al., 2025). Integrated management practices, including biochar application, optimised irrigation, and fertiliser management, improve yields (maize yields increased over 30%) while increasing SOC levels (Gv et al., 2025). These co-benefits provide immediate value to farmers, independent of carbon credit payments, addressing the concern that farmers implement practices primarily for business and sustainability reasons rather than solely for financial incentives (Barbato et al., 2023).

5. Policy Integration

Successful implementation requires supportive policy frameworks. Policy interventions should promote the adoption of best management practices through payments for ecosystem services, with improved governance and strong political will (Lal, 2015). Integration with existing government schemes such as the Soil Health Card, the National Mission for Sustainable Agriculture, and the Pradhan Mantri Fasal Bima Yojana can provide co-financing and institutional support. A National Carbon Registry for agriculture, as proposed by Gokhale et al. (2024), would facilitate the development of carbon credits and corporate investment. Policy tools should offer targeted incentives such as equipment subsidies, community-scale biochar production, and composting training through self-help groups (Patil et al., 2025).

6. Limitations and Challenges

Several challenges require careful consideration. First, portable measurement technologies, while significantly cheaper than laboratory analysis, still require initial capital investment and technical expertise. Second, carbon credit markets remain volatile, with prices subject to supply-demand dynamics and policy changes. Third, smallholder farmers face multiple competing demands on their time and resources, potentially limiting the adoption of new practices. Fourth, verification of carbon sequestration requires multi-year monitoring, creating temporal gaps between the adoption of practices and full payment. Fifth, land tenure insecurity in some regions may discourage long-term investments in soil carbon sequestration.

7. Research and Validation Needs

This paper outlines mechanisms requiring rigorous testing and validation. Key research needs include: (1) field validation of portable measurement technologies under diverse Indian soil conditions, (2) calibration of measurement equipment for regional soil types, (3) quantification of carbon sequestration rates under different management practices and agro-ecological zones, (4) assessment of farmer adoption rates and barriers under different incentive structures, (5) evaluation of SLCSO operational efficiency and financial sustainability, (6) long-term monitoring of practice permanence and carbon stock changes, and (7) economic analysis of cost-effectiveness compared to alternative carbon sequestration approaches.

VII. CONCLUSION

This research paper presents a comprehensive agricultural soil carbon credit framework specifically designed to enable Indian smallholder farmers to participate in carbon markets while improving soil health and farm productivity. By integrating low-cost measurement technologies (portable NIR spectroscopy, handheld sensors, smartphone-based tools), farmer-centric service delivery through Small Local Carbon Service Organisations, simplified incentive mechanisms with tiered payments, and the innovative Carbon Check First mechanism, this framework addresses the systematic barriers that currently exclude smallholder farmers from carbon credit programs.

The six research objectives provide a structured approach to the development, implementation, and validation of the framework. Establishing baseline data on soil organic carbon and health indicators under semi-arid conditions will create a foundation for measuring carbon sequestration and ensuring additionality. Implementing and evaluating soil management practices, such as crop residue retention and compost application, will quantify the potential for carbon sequestration while delivering co-benefits for soil health. Measuring seasonal and long-term changes in soil organic carbon will enable verification of permanence and temporal dynamics. Developing practical monitoring guidelines will empower farmers to record soil carbon improvements and participate actively in carbon credit programs.

This research framework transforms the current paradigm where farmers face upfront costs, complex procedures, and delayed payments. Instead, farmers receive free baseline assessments, affordable ongoing monitoring through local service organisations, quick initial payments for practice adoption, and transparent tracking of carbon credit generation and sales. This farmer-centric approach aligns carbon credit participation with farmers' existing motivations for improving soil health and farm sustainability.

Successful implementation of this framework could transform Indian smallholder agriculture into a significant carbon-sequestration sector while improving farmers' livelihoods. With over 146 million agricultural holdings in India, predominantly smallholder farms, the potential impact is substantial. If even 10% of smallholder farmers participate, sequestering an average of 0.5 tonnes of carbon per hectare per year, India could sequester over 7 million tonnes of carbon annually while improving soil health across millions of hectares.

This research paper tests different mechanisms to help farmers first conduct carbon baseline assessments and then proceed with the full carbon credit process. By demonstrating viability through pilot implementation, rigorous monitoring, and transparent reporting, this research aims to create a replicable model for agricultural carbon credit programs in India and other developing countries with similar smallholder farming systems. The integration of technological, institutional, and financial innovations provides a holistic solution to the complex challenge of enabling smallholder farmer participation in carbon markets while advancing climate change mitigation and sustainable agriculture goals.

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