



Blockchain-Based Carbon Credit Tracking Systems for Smallholder Farmers: A Framework for Enhancing Transparency and Market Access in Agricultural Carbon Sequestration

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Abstract

Smallholder farmers represent a critical yet underutilized component of global carbon sequestration efforts, facing systemic barriers including high transaction costs, verification complexities, and limited market access. This research develops a comprehensive blockchain-based framework designed to address these challenges through decentralized ledger technology, smart contracts, and Internet of Things integration. The proposed system incorporates multi-tiered verification protocols, tokenized carbon credits, and automated payment mechanisms to reduce intermediary dependencies while maintaining methodological rigor. Through comparative economic analysis and stakeholder assessment across three geographic regions, findings demonstrate potential transaction cost reductions of 62-68%, verification cost decreases of 76-85%, and farmer revenue increases of 200-350% compared to traditional carbon credit systems. The framework integrates satellite imagery, IoT sensors, and machine learning algorithms achieving 89% measurement accuracy at \$0.85 per hectare annually. Results indicate that blockchain implementation can democratize carbon market participation while enhancing transparency, reducing fraud, and accelerating climate finance flows to agricultural communities. This research contributes novel insights bridging technological innovation with inclusive climate action strategies.

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Introduction

Agricultural systems contribute approximately 24% of global anthropogenic greenhouse gas emissions while simultaneously offering substantial carbon sequestration potential through soil carbon storage, agroforestry, and improved land management practices^[1]. Smallholder farmers, operating 475 million farms globally and managing nearly 12% of agricultural land, represent an enormous yet largely untapped resource for climate change mitigation^[2]. Despite this potential, these farmers face disproportionate exclusion from voluntary carbon markets due to prohibitive transaction costs, complex verification requirements, inadequate technical infrastructure, and exploitative intermediary structures^[3].

Current carbon credit mechanisms predominantly favor large-scale agricultural enterprises capable of absorbing administrative costs ranging from \$20,000 to \$100,000 per project^[4]. For smallholder farmers whose average landholdings measure less than two hectares, such costs render participation economically unfeasible^[5]. Furthermore, opacity in carbon credit tracking, concerns regarding double-counting, delayed payment systems, and lack of real-time monitoring undermine market integrity and farmer confidence^[6]. Traditional carbon project aggregators, while attempting to address scale challenges, typically capture 60-70% of carbon credit value, leaving farmers with minimal economic incentives^[7].

Blockchain technology presents transformative potential to democratize carbon markets through decentralized verification, transparent transaction recording, immutable audit trails, and automated payment distribution ^[8]. Distributed ledger technology eliminates unnecessary intermediaries, reduces administrative overhead, and creates verifiable data chains that enhance market credibility ^[9]. When integrated with precision agriculture technologies, remote sensing capabilities, and Internet of Things devices, blockchain systems can provide cost-effective, scalable solutions for monitoring and verifying agricultural carbon sequestration activities ^[10].

This research addresses three critical questions: How can blockchain architecture be optimized for smallholder farmer participation in carbon credit markets? What verification protocols maintain scientific rigor while minimizing costs? How does blockchain implementation affect market access and economic outcomes for resource-constrained farming communities? The study contributes novel insights by developing a comprehensive framework integrating technological, agronomic, economic, and governance dimensions specifically designed for smallholder agricultural contexts in developing economies.

Literature Review

Carbon Markets and Smallholder Participation Barriers

Voluntary carbon markets have experienced exponential growth, with transaction values reaching \$2 billion in 2021, representing a 290% increase from previous years ^[11]. Despite this expansion, smallholder farmer participation remains marginal, typically below 5% of total agricultural carbon projects ^[12]. Research by Lipper et al. demonstrated that aggregation mechanisms and simplified monitoring, reporting, and verification protocols are essential prerequisites for inclusive carbon markets ^[13]. However, traditional aggregation models introduce additional intermediaries who extract substantial value, with farmers receiving only 10-30% of final carbon credit prices ^[14].

Agricultural carbon sequestration potential varies significantly across farming systems and geographical contexts. Regenerative agricultural practices including conservation tillage, cover cropping, integrated crop-livestock systems, and reduced fertilizer application can sequester 0.3-1.5 tonnes of CO₂ equivalent per hectare annually ^[15]. Agroforestry systems demonstrate higher sequestration rates, ranging from 1.5-3.5 tonnes CO₂e/ha/year depending on tree species composition, planting density, climatic conditions, and soil characteristics ^[16]. Yet monetizing these environmental benefits requires robust measurement, reporting, and verification systems that most smallholders cannot access independently due to technical complexity and financial constraints ^[17].

Transaction costs in carbon markets comprise multiple components including project design documentation, baseline establishment, monitoring infrastructure, third-party verification, certification fees, registry listing, and ongoing reporting requirements ^[18]. For smallholder farmers, these costs often exceed potential carbon revenue for the first 5-7 years of project implementation, creating insurmountable barriers to entry ^[19]. Additionally, information asymmetries and power imbalances in carbon value chains frequently result in exploitative contracts that undermine farmer agency and economic benefits ^[20].

Blockchain Applications in Agricultural Systems

Blockchain adoption in agriculture has focused primarily on supply chain traceability, food safety verification, and payment systems, with limited exploration of environmental credit applications ^[21]. Existing implementations demonstrate blockchain's capacity to enhance transparency in agricultural value chains, reduce food fraud through immutable provenance records, improve farmer payment timeliness, and create verifiable sustainability claims ^[22]. Smart contracts enable automated transaction execution based on predefined conditions, reducing administrative costs by 25-45% in documented agricultural applications ^[23].

Several pilot projects have explored blockchain for environmental credit systems with varying degrees of success. The IBM Food Trust initiative demonstrated distributed ledgers could track sustainability metrics across agricultural supply chains, though carbon sequestration verification remained rudimentary and lacked scientific rigor. ^[24] Howson et al. examined blockchain applications in REDD+ forest conservation projects, highlighting benefits for transparency and payment distribution but identifying significant challenges in oracle integration—the mechanisms connecting real-world environmental data to blockchain systems ^[25].

Technical barriers to blockchain implementation include energy consumption concerns, particularly for proof-of-work consensus mechanisms consuming substantial electricity, scalability limitations affecting transaction processing capacity, and user interface complexity deterring farmer adoption ^[26]. However, recent developments in proof-of-stake protocols, layer-2 scaling solutions, and mobile-first interfaces have significantly reduced these barriers, improving feasibility for agricultural applications in resource-constrained environments ^[27].

Verification Technologies and Methodological Approaches

Remote sensing technologies, including satellite imagery and unmanned aerial vehicles, offer cost-effective alternatives to ground-based carbon stock measurements ^[28]. Machine learning algorithms applied to multispectral imagery from Sentinel-2 and Landsat satellites can estimate soil organic carbon stocks with 85-92% accuracy when calibrated with regional soil databases, providing verification data suitable for carbon credit certification under major voluntary standards ^[29]. Internet of Things sensors measuring soil moisture, temperature, carbon dioxide flux, and biomass accumulation offer continuous monitoring capabilities at decreasing costs, with sensor prices declining 40% over the past five years ^[30].

Integration of monitoring technologies with blockchain systems creates opportunities for automated verification protocols that reduce human labor costs while maintaining measurement accuracy. Smart contracts can execute carbon credit issuance when sensor data and satellite imagery confirm sequestration thresholds, eliminating delays associated with manual verification processes. However, ensuring data integrity from IoT devices requires robust oracle designs, cryptographic verification, multi-source validation, and regular calibration protocols to prevent manipulation or measurement errors.

Methodology

This research employed a mixed-methods approach combining systematic literature synthesis, technological framework development, comparative economic analysis, and stakeholder assessment. The methodology comprised four integrated components designed to address research objectives while maintaining scientific rigor and practical applicability.

Framework Development Process

A blockchain-based carbon credit tracking system was designed using design science research methodology, following established guidelines for information systems development. The framework development process included stakeholder requirement analysis through structured consultations with 45 smallholder farmers, 12 carbon project developers, 8 certification body representatives, and 15 agricultural extension officers across Kenya, India, and Peru during March-August 2025. Technological architecture design incorporated Ethereum-compatible smart contracts, IPFS distributed data storage, IoT sensor integration protocols, and satellite imagery analysis pipelines. Verification protocol specifications aligned with Verified Carbon Standard and Gold Standard methodologies while optimizing for cost-efficiency. Tokenomics design addressed carbon credit representation, fractional ownership mechanisms, and marketplace liquidity requirements.

Technical Architecture Specifications

The proposed system architecture utilized a permissioned blockchain network implementing proof-of-authority consensus to balance decentralization principles with energy efficiency, transaction speed, and governance requirements. Smart contracts were developed in Solidity programming language version 0.8.19, incorporating functions for farmer registration, land parcel tokenization using geographic NFTs, carbon sequestration data recording, multi-stakeholder verification workflow management, and automated carbon credit minting upon verification confirmation. Oracle integration employed Chainlink decentralized networks to connect off-chain sensor data, satellite imagery analysis results, and field verification reports with on-chain verification processes while maintaining data integrity.

Monitoring protocols integrated three complementary data sources to enhance measurement accuracy and reduce fraud risk. Satellite-based remote sensing utilized Sentinel-2 multispectral imagery with 10-meter spatial resolution for vegetation indices including NDVI and EVI, land use change detection, and biomass estimation. IoT soil sensors deployed at representative sampling points measured carbon content through spectroscopic analysis, soil moisture, temperature, and pH at 15-day intervals, transmitting encrypted data via LoRaWAN networks. Periodic field verification through trained local agronomists conducted stratified random sampling across 10% of registered parcels annually, providing ground-truth calibration for automated monitoring systems.

Verification Protocol Design

A three-tiered verification approach balanced cost-efficiency with credibility requirements and buyer confidence. Tier 1 verification relied on automated analysis of satellite imagery and IoT sensor data using machine learning algorithms

trained on regional soil carbon databases containing over 50,000 soil samples. Random forest regression models predicted carbon stock changes with cross-validated R^2 values exceeding 0.85 across diverse agroecological zones. Tier 2 verification incorporated third-party validation through accredited local verification bodies conducting field assessments for project aggregations exceeding 1,000 tCO_{2e} annually or upon buyer request. Tier 3 verification engaged international certification bodies for projects seeking premium carbon credit prices, compliance market eligibility, or certification under Gold Standard requirements.

Economic Analysis Methodology

Comparative cost-benefit analysis evaluated the proposed blockchain system against traditional carbon project development approaches using net present value calculations over 10-year time horizons with 8% discount rates reflecting agricultural investment risk profiles. Transaction cost components were itemized including registration fees, baseline assessment, monitoring equipment purchase and maintenance, verification expenses, intermediary commissions, administrative overhead, and registry listing fees. Carbon credit price scenarios ranged from \$5 to \$25 per tCO_{2e} based on current voluntary market prices and projected future demand. Sensitivity analysis examined framework economic viability under varying adoption rates, technology cost trajectories, carbon sequestration rates, and market price fluctuations using Monte Carlo simulation with 10,000 iterations.

Data Collection and Analysis

Primary data collection involved structured surveys administered to 156 smallholder farmers across three geographic regions assessing technological literacy, smartphone ownership, internet connectivity, carbon sequestration potential based on current practices, and willingness to participate in blockchain-based carbon markets. Secondary data sources included carbon credit registry databases, agricultural statistics from national governments, satellite imagery archives, and academic literature on carbon accounting methodologies. Quantitative analysis employed descriptive statistics, regression modeling to identify factors influencing participation feasibility, and comparative analysis of economic outcomes across implementation scenarios.

Results and Discussion

Framework Architecture and Core Components

The developed blockchain-based carbon credit tracking system comprises five interconnected modules addressing specific barriers in current carbon market structures while maintaining compatibility with existing certification standards (Table 1). The registration and identity module implements self-sovereign identity protocols allowing farmers to create verifiable digital credentials without centralized databases, addressing privacy concerns while enabling regulatory compliance and fraud prevention. Land parcel tokenization employs non-fungible tokens encoding geographic coordinates as polygon boundaries, enabling precise carbon accounting at field level and facilitating seamless project aggregation across multiple smallholders without complex legal agreements.

Table 1: Blockchain-Based Carbon Credit System Architecture and Module Specifications

Module	Primary Functions	Technology Components	Implementation Benefits
Registration & Identity	Farmer profile creation, credential verification, baseline establishment	Self-sovereign identity, zero-knowledge proofs, encrypted storage	70% cost reduction; eliminates documentation barriers
Land Tokenization	Boundary recording, ownership verification, smart contract deployment	Geographic NFTs, polygon encoding, immutable registry	Prevents tenure disputes; enables micro-project aggregation
Monitoring System	Data collection, automated analysis, anomaly detection	IoT sensors, satellite APIs, ML carbon models	85% monitoring cost reduction; real-time verification
Verification Engine	Multi-tier validation, consensus protocols, audit trail generation	Oracle networks, validator nodes, IPFS documentation	76% verification cost decrease; enhanced transparency
Credit Market	Automated minting, trading infrastructure, payment distribution	ERC-20 tokens, DEX integration, smart escrow	Eliminates intermediaries; 200-350% revenue increase

The carbon monitoring system achieved 89% agreement with ground-truth measurements across 234 validation plots while reducing monitoring costs to \$0.85 per hectare annually compared to conventional field-based approaches averaging \$11.50 per hectare. Machine learning models trained on regional databases predicted soil carbon stock changes with R² values ranging from 0.82 to 0.91 across different agroecological zones. Integration of multiple data sources—satellite imagery, IoT sensors, and periodic field validation—improved estimation accuracy by 15-23% compared to single-source approaches while maintaining cost-effectiveness.

Economic Performance and Cost Analysis

Table 2: Comparative Economic Analysis of Carbon Project Development Approaches (100-hectare project, 10-year period)

Cost Component	Traditional System	Blockchain Framework	Reduction (%)
Project Design & Registration	\$3,200	\$800	75%
Baseline Assessment	\$4,500	\$1,200	73%
Monitoring (annual)	\$1,150	\$170	85%
Verification & Certification (annual)	\$5,800	\$1,400	76%
Intermediary Fees (% of credit value)	50% average	10% average	80%
Administrative Overhead (annual)	\$2,150	\$450	79%
Total NPV (10 years, 8% discount)	\$68,400	\$21,800	68%
Farmer Revenue per tCO ₂ e	\$3-8	\$12-17	250%

Break-even analysis demonstrated that blockchain implementation reduced minimum viable carbon prices from \$12-15 per tCO₂e in traditional systems to \$4-6 per tCO₂e, expanding feasible participation to farmers practicing moderate-intensity carbon sequestration activities. Sensitivity analysis incorporating uncertainty across multiple parameters showed positive net present values in 87% of simulated scenarios, indicating robust economic viability across diverse contexts. Even under conservative assumptions—low adoption rates, high technology costs, and depressed carbon prices—the blockchain framework maintained superior cost-effectiveness compared to conventional approaches in 73% of scenarios.

Verification Protocol Performance and Accuracy

The three-tiered verification system achieved balance between cost-efficiency and measurement accuracy sufficient for voluntary carbon market requirements. Tier 1 automated verification utilizing satellite imagery and IoT sensors demonstrated mean absolute error of 0.12 tCO₂e/ha compared to intensive field sampling, well within the 10% uncertainty threshold established by major carbon standards. Normalized Difference Vegetation Index and Enhanced Vegetation Index derived from Sentinel-2 imagery served as

Comparative economic analysis revealed substantial advantages for blockchain-based systems across all cost categories (Table 2). Total project development costs decreased by 68% on average, primarily through elimination of intermediary fees and reduction in verification expenses. For a representative 100-hectare smallholder aggregation project sequestering 0.8 tCO₂e/ha/year, total establishment and 10-year operational costs totaled \$21,800 under the blockchain framework versus \$68,400 for conventional approaches. Most significantly, farmers captured 80-85% of carbon credit value compared to 20-40% under traditional systems, translating to revenue increases of \$12-17 per tCO₂e versus \$3-8 per tCO₂e.

strong predictors of above-ground biomass accumulation in agroforestry systems with correlation coefficients of 0.76-0.84. Soil organic carbon estimation models incorporating spectral reflectance, temperature, and moisture data achieved prediction accuracy of 88-93% across validation datasets. Tier 2 verification through local validation bodies conducting field assessments at 10% sampling intensity cost \$4.20 per hectare while providing quality assurance and local employment opportunities. Discrepancy rates between Tier 1 automated verification and Tier 2 field validation averaged 8.3%, demonstrating reliability of automated systems. Tier 3 international certification, while expensive at \$15-25 per hectare, enabled access to premium carbon credit markets and compliance frameworks, justifying costs for large-scale projects or those seeking Gold Standard certification.

Stakeholder Assessment and Adoption Considerations

Structured surveys of 156 smallholder farmers revealed moderate technological readiness with significant variation across geographic contexts. Mobile phone ownership exceeded 82% across surveyed populations, but smartphone penetration ranged from 42% in rural Kenya to 71% in peri-urban India, indicating infrastructure prerequisites for implementation. Approximately 68% of respondents

expressed interest in carbon credit programs when benefits were explained, while only 34% reported confidence in using blockchain-based systems without technical support, underscoring the necessity of comprehensive training programs and user-friendly mobile interfaces.

Digital literacy emerged as a critical adoption barrier, with 58% of respondents having limited experience with digital financial systems beyond basic mobile money transfers. Successful implementation requires mobile applications with simplified interfaces, local language support, offline functionality for areas with intermittent connectivity, and integration with existing agricultural extension services. Trust concerns regarding new technologies and unfamiliarity with carbon markets affected 45% of respondents, reflecting broader trust deficits in agricultural value chains. Pilot projects implementing blockchain systems through established farmer cooperatives demonstrated 40% higher

adoption rates compared to direct individual farmer engagement, suggesting existing social structures provide important trust-building mechanisms.

Environmental Integrity and Governance Framework

Maintaining environmental integrity standards, particularly additionality and permanence, required careful protocol design within blockchain systems (Table 3). Additionality was established through baseline comparisons using historical land use data from satellite imagery archives and regional agricultural practice databases. Smart contracts encoded additionality criteria specific to geographic contexts, preventing credit issuance for practices already widespread in specific regions. Dynamic baseline adjustments incorporated regional adoption trends, ensuring credits represented genuine climate benefits beyond business-as-usual trajectories.

Table 3: Environmental Integrity Mechanisms and Implementation Protocols

Integrity Principle	Implementation Mechanism	Verification Method	Governance Structure
Additionality	Historical baseline analysis; regional practice comparison	Satellite imagery archives; agricultural census data	Multi-stakeholder review committee
Permanence	20% buffer pool; minimum 10-year monitoring commitment	Continuous satellite monitoring; automated reversal detection	Smart contract-managed buffer reserve
Leakage Prevention	Geographic boundary definition; displacement monitoring	Land use change detection; regional production analysis	Third-party validation protocols
Double-Counting Prevention	Unique tokenization; registry synchronization	Blockchain immutability; cross-registry verification	Distributed consensus validation

Permanence concerns, particularly relevant for soil carbon sequestration subject to reversal through management changes, were addressed through buffer pool mechanisms and monitoring continuity requirements. The framework allocated 20% of issued carbon credits to a collective buffer pool managed through smart contracts, which compensated for reversals detected through continued monitoring. Farmers committing to minimum 10-year monitoring periods received premium payments of 15-25% above spot carbon prices, incentivizing long-term carbon stewardship while reducing reversal risk.

Multi-stakeholder governance incorporated farmer representatives, technical service providers, certification bodies, carbon credit buyers, and development organizations in consensus decisions regarding protocol updates, dispute resolution, and buffer pool management. Smart contract upgradeability mechanisms enabled system improvements while maintaining transaction history immutability and preventing retroactive manipulation. Quarterly governance meetings conducted via digital platforms ensured distributed decision-making authority while maintaining operational efficiency.

Scalability and Technical Performance

Blockchain network performance analysis examined transaction processing capacity under various adoption scenarios. The proposed permissioned blockchain architecture utilizing proof-of-authority consensus achieved transaction throughput of 1,800-2,200 transactions per second during stress testing, sufficient to accommodate carbon credit issuance and trading for approximately 500,000 smallholder farmers conducting monthly monitoring updates. Average transaction confirmation time measured 3-5 seconds with network latency below 200 milliseconds across distributed nodes in Kenya, India, and Peru.

Layer-2 scaling solutions including state channels for high-frequency monitoring data and optimistic rollups for verification processes provided additional capacity expansion pathways if broader adoption necessitated increased throughput. Gas fees for transaction processing averaged \$0.008-0.015 per transaction under normal network conditions, representing negligible costs relative to carbon credit values. Energy consumption for the proof-of-authority network totaled approximately 0.12 kWh per transaction, equivalent to 0.00008 tCO_{2e}, representing less than 0.01% of typical agricultural carbon credits verified through the system.

Market Integration and Regulatory Considerations

Integration with existing carbon credit registries and compliance frameworks presented both opportunities and challenges for widespread adoption. The blockchain framework was designed for interoperability with Verra Registry, Gold Standard, and Climate Action Reserve through standardized data export formats, API connectivity, and dual registration protocols. However, regulatory recognition of blockchain-based carbon credits varied substantially across jurisdictions, with progressive governments in Switzerland, Singapore, and Kenya explicitly supporting distributed ledger implementations while conservative regulators in other contexts maintained traditional registry requirements exclusively.

Tokenized carbon credits represented as fungible ERC-20 tokens enabled fractional trading, automated market-making through decentralized exchanges, and integration with emerging decentralized finance protocols. Minimum viable liquidity pools required approximately \$75,000-100,000 in paired assets—carbon credit tokens and stablecoins—to facilitate efficient price discovery and minimize slippage during trading. Initial liquidity provision through

development finance institutions, impact investors, and corporate sustainability programs catalyzed market formation during early implementation phases, with gradual transition to self-sustaining liquidity as farmer participation expanded.

Conclusion

This research developed and evaluated a comprehensive blockchain-based framework for carbon credit tracking specifically designed to address systemic barriers preventing smallholder farmer participation in voluntary carbon markets. The proposed system demonstrated substantial improvements across economic, technical, and social dimensions compared to traditional carbon project development approaches. Cost reductions of 62-68% in total project expenses, verification cost decreases of 76-85%, and farmer revenue increases of 200-350% established strong economic viability while automated monitoring achieving 89% measurement accuracy maintained scientific credibility. The framework's integration of distributed ledger technology, smart contracts, IoT sensors, satellite imagery, and machine learning algorithms created an ecosystem enabling transparent, cost-effective, and scalable agricultural carbon credit systems. Multi-tiered verification protocols balanced measurement accuracy with cost-efficiency, while governance structures incorporating distributed decision-making authority addressed power imbalances inherent in traditional carbon value chains. Environmental integrity mechanisms including additionality verification, permanence monitoring, buffer pools, and double-counting prevention maintained alignment with established carbon accounting standards.

Implementation challenges including digital literacy barriers, technological infrastructure requirements, regulatory uncertainty, and initial capital requirements for sensor deployment and liquidity provision require coordinated interventions involving governments, development organizations, technology providers, and farmer organizations. Successful scaling depends on agricultural extension service integration, comprehensive training programs, user-friendly mobile interfaces, cooperative-based implementation models, and supportive regulatory frameworks recognizing blockchain-based carbon credits.

Future research should investigate long-term system performance across diverse agroecological zones, examine behavioral responses to automated payment systems, assess carbon market price dynamics under increased smallholder participation, and explore integration with other ecosystem service payment schemes including biodiversity conservation and water quality enhancement. Longitudinal studies tracking farmer adoption patterns, income effects, and land management changes will provide critical insights for refining implementation strategies and maximizing climate and development co-benefits.

This research contributes to sustainable agriculture and climate finance literature by demonstrating technological pathways for democratizing carbon markets while enhancing transparency, reducing fraud, accelerating payment flows, and empowering marginalized agricultural communities. As voluntary carbon markets continue expanding and pressure intensifies for credible, verifiable climate action, blockchain-based frameworks offer practical solutions for mobilizing smallholder farmers as crucial allies in global climate change mitigation efforts.

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