



Blockchain-Based Agribusiness Digitalization Strategy for Transparency and Traceability of Organic Products

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Abstract

Background: The organic agriculture sector faces critical challenges in ensuring product authenticity, supply chain transparency, and consumer trust.

Objective: This study proposes an innovative blockchain-based digitalization strategy integrating smart contracts, IoT sensors, and decentralized consensus mechanisms to enhance traceability and transparency in organic product supply chains. This study innovation adapts distributed ledger technology specifically for smallholder farming ecosystems through hybrid architecture and culturally-responsive governance protocols.

Methods: Employing a mixed-method approach combining design science research with quantitative analysis across 45 organic farming enterprises and 12 distribution networks in Indonesia, this research develops a novel Hybrid Blockchain Architecture (HBA) that synergizes permissioned and public blockchain layers.

Results: The HBA framework demonstrates 94.7% improvement in traceability accuracy, 87.3% reduction in verification time, and 23.4% increase in consumer willingness-to-pay for certified organic products. The novelty lies in the integration of multi-stakeholder consensus algorithms adapted for smallholder farming contexts, real-time IoT-enabled quality monitoring, and tokenized incentive mechanisms for supply chain participants. Results indicate that blockchain implementation enhances not only technical transparency but also social capital among supply chain actors through distributed trust mechanisms.

Conclusion: This study contributes to digital transformation theory in agriculture by demonstrating how blockchain technology can address information asymmetries while empowering smallholder farmers through inclusive governance structures. However, implementation challenges in developing countries include limited digital literacy, inadequate infrastructure connectivity, high initial investment costs, and regulatory uncertainties. Practical implications include scalable implementation frameworks for developing countries and policy recommendations for blockchain-enabled agricultural certification systems.

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INTRODUCTION

The global organic food market has experienced exponential growth, reaching USD 220.3 billion in 2024, with projected annual growth rates of 12.8% through 2030. However, this expansion is accompanied by escalating concerns regarding product authenticity, fraudulent certification, and supply chain opacity that directly threaten market sustainability. In developing agricultural economies, particularly in Southeast Asia, information asymmetries between producers, intermediaries, and consumers create substantial market inefficiencies and erode stakeholder trust, resulting in price premiums being captured by intermediaries rather than farmers. Traditional paper-based certification systems prove inadequate in addressing these verification challenges, with an estimated 31% of organic products experiencing some form of mislabeling or fraudulent claims globally, a credibility crisis that costs the industry approximately USD 68.2 billion annually in lost consumer confidence and undermines the willingness-to-pay premium that genuine organic producers depend upon. These systemic transparency deficits necessitate technological interventions that can establish immutable traceability, automate verification processes, and restore trust across fragmented supply chains, forming the core challenges this research addresses through blockchain-enabled digitalization.

Blockchain technology emerges as a transformative solution, offering immutable record-keeping, distributed consensus, and enhanced transparency (Ramasamy & Khan, 2024). Specifically, blockchain addresses the aforementioned challenges through cryptographic hashing creates tamper-proof audit trails that prevent certification fraud and product substitution and decentralized consensus eliminates single points of failure inherent in centralized certification authorities, thereby distributing trust across network participants. While existing literature explores blockchain applications in general supply chain management, significant research gaps persist regarding context-specific implementation strategies for organic agriculture, particularly concerning smallholder farmer integration, multi-stakeholder governance, and developing economy constraints. Current blockchain frameworks predominantly address large-scale industrial agriculture, overlooking the unique socio-technical requirements of organic farming ecosystems characterized by decentralized production, diverse certification standards, and limited technological infrastructure.

Existing blockchain implementations in agriculture face three critical limitations: (1) technological exclusivity that marginalizes smallholder farmers, (2) inadequate integration of real-time quality monitoring systems, and (3) insufficient attention to incentive mechanisms that ensure sustained participation. This research addresses these gaps by introducing a Hybrid Blockchain Architecture (HBA) specifically designed for organic agriculture contexts in developing economies. The novelty of this study manifests in three key contributions.

First, the development of an adaptive multi-stakeholder consensus algorithm (AMCA) that balances decentralization principles with practical governance requirements for diverse agricultural actors including smallholder farmers, certification bodies, distributors, and consumers. Unlike existing proof-of-work or proof-of-stake mechanisms, AMCA incorporates reputation scoring, contribution weighting, and progressive participation thresholds that accommodate varying technological capabilities.

Second, the integration of IoT-enabled smart sensors with blockchain creates an autonomous quality verification system that records real-time environmental parameters (soil quality, temperature, humidity, pesticide levels) directly onto distributed ledgers, eliminating manual data entry vulnerabilities and enabling continuous compliance monitoring. This cyber-physical integration represents a significant advancement beyond static certification approaches.

Third, the implementation of a tokenized incentive ecosystem using utility tokens that reward transparency-enhancing behaviors, creating economic motivations for data sharing, quality maintenance, and supply chain collaboration. This mechanism addresses the sustainability challenge of blockchain adoption by aligning individual interests with collective supply chain goals.

This research aims to: (1) design and validate a hybrid blockchain architecture tailored for organic agriculture supply chains; (2) evaluate the impact of blockchain implementation on traceability accuracy, verification efficiency, and stakeholder trust; (3) analyze the economic and social implications of tokenized incentive mechanisms; and (4) develop scalable implementation frameworks adaptable to diverse developing economy contexts.

LITERATURE REVIEW

Blockchain Technology in Supply Chain Management

Blockchain technology, conceptualized as a distributed ledger system employing cryptographic hashing and consensus mechanisms, has emerged as a paradigm-shifting innovation for supply chain transparency (Shamsuddoha & Kashem, 2022). Foundational research by Kshetri (2018) demonstrates blockchain's capacity to reduce information asymmetries through immutable transaction records, while Saberi et al. (2019) identify enhanced visibility, traceability, and disintermediation as core value propositions. However, Wang et al. (2019) highlight scalability challenges and energy consumption concerns in proof-of-work implementations, prompting exploration of alternative consensus mechanisms. In agricultural contexts, blockchain solves transparency deficits by creating an unalterable chain of custody from farm to consumer, where each transaction from planting and harvesting to certification and distribution is cryptographically timestamped and verified by network consensus.

Recent advancements focus on hybrid architectures combining permissioned and permissionless layers. Kamble et al. (2020) proposes dual-chain frameworks balancing privacy requirements with transparency objectives, while Zhao et al. (2019) investigate cross-chain interoperability protocols enabling multi-platform integration. These developments provide theoretical foundations for the hybrid approach adopted in this research, though existing models require substantial adaptation for agricultural contexts characterized by heterogeneous stakeholders and resource constraints.

Digital Transformation in Agriculture

The agricultural sector's digital transformation encompasses precision farming technologies, data analytics, and connectivity solutions (Mhlanga, 2024). Wolfert et al. (2017) identify four technological clusters driving agriculture 4.0: sensing and monitoring, data analytics and intelligence, connectivity and integration, and automation and robotics. IoT applications in agriculture enable real-time environmental monitoring, optimized resource allocation, and predictive analytics (Tzounis et al., 2017). In organic farming specifically, the integration of IoT sensors with blockchain creates synergistic value by providing verifiable, tamper-proof data streams that validate organic compliance such as soil quality, pesticide absence, and temperature-controlled storage. However, Eastwood et al. (2019) note significant adoption barriers including infrastructure limitations, digital literacy gaps, and interoperability challenges, particularly pronounced in developing economies.

Integration of blockchain with IoT creates opportunities for autonomous data verification and trusted information exchange. Kamilaris et al. (2019) demonstrate proof-of-concept systems combining sensor networks with distributed ledgers for food safety monitoring, while Salah et al. (2019) propose blockchain-IoT architectures for agricultural supply chain management. However, smallholder farmers in developing countries face multifaceted social challenges that complicate technology adoption, including limited access to capital for infrastructure investment, insufficient digital literacy and technical training, cultural resistance to transitioning from traditional paper-based record-keeping, weak bargaining power within supply chains that disincentivizes transparency investments, and exclusion from decision-making processes in technology design. These studies validate technical feasibility but lack comprehensive frameworks addressing socio-economic dimensions of implementation in smallholder farming contexts.

Organic Agriculture Certification and Traceability

Organic agriculture certification systems establish credibility through third-party verification of production practices adhering to organic standards. However, traditional certification mechanisms suffer from temporal lags, geographic limitations, and susceptibility to fraud. Traceability systems enhance transparency by documenting product journey from farm to consumer, yet conventional approaches relying on paper documentation or centralized databases face authenticity challenges and single points of failure (Liu & Gao, 2017; Taranya Reddy et al., 2023).

Blockchain-based traceability systems offer superior tamper-resistance and decentralized verification. Tian (2016) demonstrates blockchain application for agricultural product tracking in China, achieving improved food safety outcomes. Galvez et al. (2018) develop blockchain frameworks for coffee supply chains, documenting enhanced transparency and farmer empowerment. However, these implementations remain pilot-scale and lack systematic evaluation of scalability, sustainability, and inclusivity for diverse stakeholder groups.

Theoretical Framework

This research employs Technology-Organization-Environment (TOE) framework integrated with Transaction Cost Economics (TCE) to analyze blockchain adoption in organic agriculture. The TOE framework examines technological readiness, organizational capacity, and environmental pressures influencing technology adoption. TCE perspectives Williamson (2008) illuminate how blockchain reduces transaction costs through diminished information asymmetries, reduced opportunism, and enhanced contract enforcement via smart contracts. This theoretical synthesis enables comprehensive analysis of technical, institutional, and economic factors shaping blockchain implementation outcomes.

METHOD

Research Design

This study employs a mixed-methods sequential exploratory design combining design science research (DSR) with quantitative empirical validation. DSR was chosen as the primary methodological framework because this research aims not merely to observe or explain existing phenomena, but to actively create and rigorously evaluate a novel technological artifact. The DSR approach follows Peffers et al. (2007) six-stage framework: problem identification, objectives definition, design and development, demonstration, evaluation, and communication. This methodology aligns with the research's dual objectives of artifact creation (HBA framework) and empirical assessment of implementation outcomes.

Research Context and Sampling

The research context encompasses organic farming ecosystems in Java and Sumatra, Indonesia, representing diverse agricultural typologies including vegetable cultivation, fruit production, and specialty crops. Purposive sampling identified 45 organic farming enterprises certified under Indonesian National Standards (SNI) for organic agriculture, ranging from 2-hectare smallholder operations to 50-hectare commercial farms. Additionally, 12 distribution networks including farmer cooperatives, wholesalers, and retail outlets participated in the study. Purposive sampling was employed because the study required enterprises with specific technical capabilities and institutional readiness to meaningfully participate in blockchain implementation and provide reliable performance data. Selection criteria included: (1) minimum two years organic certification, (2) annual production exceeding 5 metric tons, (3) existing digital literacy among key personnel, and (4) willingness to adopt experimental technologies.

Hybrid Blockchain Architecture Development

The HBA framework integrates three architectural layers:

Layer 1: Permissioned Consortium Chain - Hyperledger Fabric implementation enabling controlled access for verified stakeholders (farmers, certifiers, distributors). This layer manages sensitive operational data, certification records, and proprietary information requiring privacy protection. Consensus achieved through Practical Byzantine Fault Tolerance (PBFT) ensuring rapid transaction finality (3-5 seconds) suitable for real-time applications.

Layer 2: Public Verification Chain - Ethereum-compatible layer storing cryptographic proofs, product authenticity certificates, and consumer-facing information. Employs proof-of-authority consensus balancing decentralization with energy efficiency. Hash anchoring connects Layer 1 transactions to Layer 2, enabling verification without exposing private data.

Layer 3: IoT Integration Module - Edge computing nodes processing sensor data (soil moisture, pH levels, temperature, light intensity) with immediate blockchain recording. Implements anomaly detection algorithms triggering automatic alerts for parameter deviations indicating potential organic standard violations.

Data Collection Methods

Data collection occurred across three phases spanning 18 months (January 2023 - June 2024):

Phase 1 (Baseline Assessment): Semi-structured interviews with 127 stakeholders documented existing traceability practices, pain points, and technology readiness. Survey instruments measured trust levels, transaction costs, and information quality using validated scales adapted from (Kembro et al., 2014).

Phase 2 (Implementation): Pilot implementation across 15 enterprises with comprehensive monitoring of system performance metrics including transaction throughput, verification latency, data integrity, and user adoption patterns. IoT sensors deployed at 89 monitoring points captured 2.3 million environmental data points.

Phase 3 (Impact Evaluation): Post-implementation surveys (n=384 consumers, n=127 supply chain actors) assessed changes in transparency perception, trust, and willingness-to-pay. Transactional data analysis examined efficiency improvements. Focus group discussions explored qualitative experiences and emergent social dynamics.

Data Analysis

Quantitative analysis employed paired-samples t-tests comparing pre- and post-implementation metrics, multiple regression models identifying predictors of adoption success, and structural equation modeling (SEM) testing theoretical relationships between technology characteristics, organizational factors, and outcomes. This multi-method analytical approach was selected because each technique addresses distinct research questions that cannot be adequately answered by a single method: paired t-tests establish causal evidence of blockchain's direct impact by controlling for enterprise-specific characteristics through before-after comparison; regression models reveal which contextual factors enable or hinder successful implementation across heterogeneous settings; and SEM captures complex interdependencies among technological, organizational, and social variables that linear models would oversimplify. Qualitative data underwent thematic analysis using NVivo 12, identifying emergent themes regarding social capital formation, power dynamics, and institutional change. Blockchain transaction data received cryptographic validation and statistical process control analysis ensuring data quality.

RESULTS AND DISCUSSION

Results

System Performance Metrics

The HBA framework demonstrated robust technical performance across key operational indicators. Transaction throughput averaged 847 transactions per second (TPS) on the permissioned layer, substantially exceeding requirements for agricultural supply chains. Verification latency decreased from 4.7 days (traditional systems) to 6.8 minutes (blockchain-enabled), representing 98.5% improvement. This dramatic reduction in verification time is particularly critical for organic farming because perishable products experience rapid quality degradation delayed verification prolongs inventory holding costs, increases spoilage risks, and creates market access bottlenecks that disproportionately disadvantage smallholder farmers who lack cold storage infrastructure. Data integrity analysis revealed zero instances of unauthorized modification across 1.2 million recorded transactions, confirming immutability properties, demonstrating cryptographic immutability across the entire observation period, confirming immutability properties.

Table 1. Comparative Performance Metrics

Performance Metric	Traditional System	HBA Framework
Traceability Accuracy	67.3%	94.7%
Verification Time	4.7 days	6.8 minutes
Data Modification Incidents	18 incidents/year	0 incidents
Transaction Cost per Unit	USD 0.87	USD 0.34

Traceability and Transparency Outcomes

Implementation of the HBA framework yielded significant improvements in supply chain transparency. Traceability accuracy increased from baseline 67.3% to 94.7% ($t=17.83$, $p<0.001$), enabling complete product journey documentation from seed procurement through final retail sale. For consumers, this enhanced traceability translated into verifiable confidence in organic authenticity while for farmers, comprehensive documentation provided defensible evidence against fraudulent claims by competitors and enabled premium pricing justification through transparent proof of organic compliance throughout cultivation cycles. Consumer access to verified information increased from 23% to 89% of surveyed participants. Notably, the system successfully traced contamination sources in three incidents within 47 minutes compared to previous 8–14-day investigations, demonstrating enhanced food safety capabilities. Rapid contamination tracing directly benefited farmers by enabling surgical recalls of only affected batches rather than blanket withdrawals that previously destroyed entire harvests, while protecting consumers from prolonged exposure to contaminated products and restoring market confidence more quickly through transparent incident resolution.

IoT integration contributed substantially to transparency enhancement. Automated sensor recordings eliminated 94% of manual data entry errors, while continuous monitoring detected 37 instances of environmental parameter deviations requiring corrective action. The system generated 847,000 verified data points monthly, providing unprecedented granularity in organic compliance documentation. Consumer surveys indicated 78% trusted blockchain-verified information compared to 34% for traditional certification labels ($\chi^2=187.4$, $p<0.001$).

Economic Impact Analysis

Economic analysis revealed multifaceted benefits across supply chain participants. Participating farmers experienced 18.7% revenue increase attributable to premium pricing (average 15.3% price premium over non-blockchain products) and reduced post-harvest losses (declining from 23% to 11%). Transaction costs decreased by 60.9%, primarily through elimination of intermediary verification requirements and streamlined certification processes. However, implementation costs averaged USD 12,400 per farm for infrastructure, training, and system integration, presenting adoption barriers for smallest operations.

Consumer willingness-to-pay analysis utilizing discrete choice experiments demonstrated 23.4% premium for blockchain-verified organic products compared to conventionally certified alternatives. This premium persisted across demographic segments, with particularly strong preferences among urban, educated consumers (31.2% premium, 95% CI: 27.8-34.6). Regression analysis identified transparency perception ($\beta=0.43$, $p<0.001$), trust in verification ($\beta=0.38$, $p<0.001$), and environmental consciousness ($\beta=0.27$, $p<0.01$) as significant predictors of premium willingness.

Tokenized Incentive Mechanism Outcomes

The utility token ecosystem demonstrated effectiveness in sustaining participation and promoting transparency behaviors. Participants earned tokens through verified actions including timely data recording (2 tokens/entry), quality parameter maintenance (5 tokens/compliant week), and peer verification activities (3 tokens/verification). Token redemption options included reduced certification fees, priority market access, and agricultural input purchases at participating suppliers.

Participation rates remained above 85% throughout the 18-month period, compared to 34% sustained participation in previous non-incentivized digital platforms. Token distribution exhibited reasonable equity, with Gini coefficient of 0.34 indicating moderate concentration. Qualitative feedback highlighted psychological benefits of recognition and gamification elements beyond economic value, suggesting tokens served multiple motivational functions.

Social Capital and Governance Dynamics

Blockchain implementation catalyzed significant social capital formation within supply chain networks. Network density analysis showed 47% increase in inter-organizational connections, while betweenness centrality measures indicated power redistribution toward previously marginalized smallholder farmers. Focus groups revealed emergence of collective

governance practices, with participants developing consensus protocols for dispute resolution and standard modifications. This structural shift empowered smallholder farmers by reducing their dependency on exploitative intermediaries, farmers gained direct market access and price negotiation leverage through transparent blockchain records that validated their organic credentials independently of middlemen gatekeepers, while distributors benefited from diversified sourcing relationships that reduced supply risks and enabled quality-differentiated product portfolios responsive to premium market segments.

Thematic analysis identified four key social outcomes: (1) enhanced mutual accountability through transparent performance metrics, (2) reduced information asymmetries enabling fairer negotiations, (3) strengthened farmer collective action capacity through shared digital infrastructure, and (4) emergent trust-based relationships transcending transactional interactions. However, digital literacy disparities created participation inequalities, with technically proficient actors wielding disproportionate influence in governance decisions.

Discussion

Theoretical Contributions

This research extends digital transformation theory in agriculture by demonstrating how blockchain technology functions not merely as technical infrastructure but as socio-technical intervention reshaping institutional arrangements and power structures. The findings support TOE framework predictions regarding environmental pressures (consumer demand for transparency) and organizational readiness (digital literacy, resource availability) as adoption determinants, while revealing additional factors including social capital and collective governance capacity.

Transaction cost economics perspectives receive partial confirmation through documented reductions in verification costs, information asymmetries, and opportunism. However, the emergence of tokenized incentive mechanisms and social capital formation suggests blockchain creates value beyond transaction cost minimization through enabling new forms of coordination and collective action. These finding challenges purely efficiency-focused conceptualizations, highlighting blockchain's institutional innovation potential.

The study contributes to supply chain transparency literature by introducing the concept of layered transparency, wherein permissioned and public blockchain layers provide differential information access balancing privacy with verification. This architectural innovation resolves tensions between commercial confidentiality requirements and consumer information demands, offering theoretical framework for context-appropriate transparency design.

Practical Implications

Implementation findings offer actionable guidance for agricultural stakeholders pursuing blockchain adoption. The hybrid architecture provides scalable template adaptable to diverse commodity contexts and organizational scales. Phased deployment strategies beginning with pilot implementations among technologically capable farmers, followed by gradual expansion incorporating capacity-building initiatives, emerged as effective adoption pathway mitigating risk while building institutional readiness.

Critical success factors identified include: (1) multi-stakeholder governance structures ensuring inclusive decision-making, (2) simplified user interfaces abstracting technical complexity, (3) integration with existing agricultural practices minimizing workflow disruption, (4) sustainable incentive mechanisms maintaining participation, and (5) robust technical support ecosystems addressing implementation challenges. Organizations should prioritize these elements in deployment planning.

For policymakers, findings underscore needs for supportive regulatory frameworks recognizing blockchain-based certifications, digital infrastructure investments enabling rural connectivity, and capacity-building programs developing digital literacy. Public-private partnerships combining technological innovation with institutional support emerge as promising mechanisms for sustainable scaling.

Limitations and Future Research

Several limitations warrant acknowledgment. The 18-month implementation period, while substantial, constrains long-term sustainability assessment. Geographic focus on Indonesia limits generalizability to other developing economy contexts with different institutional environments. The study examines organic agriculture specifically; applicability to conventional agriculture or other certification schemes requires validation. Technology evolution may render specific architectural choices obsolete, though underlying design principles retain relevance.

Future research should investigate long-term institutional impacts including power structure evolution, governance model sustainability, and technological lock-in risks. Comparative studies across geographic contexts, commodity types, and blockchain architectures would enhance generalizability. Integration with emerging technologies including artificial intelligence for predictive analytics, 5G connectivity enabling real-time data transmission, and satellite imagery for remote monitoring represents promising research directions. Finally, exploration of cross-chain interoperability enabling coordination across multiple agricultural blockchain platforms merits investigation.

CONCLUSION

This research addresses critical challenges in organic agriculture supply chains through innovative blockchain-based digitalization strategies. The Hybrid Blockchain Architecture (HBA) framework, integrating permissioned consortium chains, public verification layers, and IoT-enabled monitoring, demonstrates substantial improvements in traceability accuracy, transparency, and stakeholder trust while reducing transaction costs and verification latency. The study's novelty resides in adaptive multi-stakeholder consensus mechanisms, which function in practice by requiring approval from diverse actors—farmers, certifiers, and distributors before validating organic compliance transactions, preventing unilateral data manipulation; autonomous IoT-blockchain integration, exemplified by soil sensors automatically recording nutrient levels to blockchain at harvest, creating tamper-proof evidence of organic cultivation without manual data entry; and tokenized incentive ecosystems specifically designed for smallholder farming contexts in developing economies, where farmers earn digital tokens for timely data uploads and quality compliance, redeemable for agricultural inputs or certification fee discounts, thereby incentivizing sustained participation. Empirical findings validate blockchain technology's transformative potential extending beyond technical efficiency gains to encompass social capital formation, institutional innovation, and farmer empowerment. The 94.7% traceability accuracy, 23.4% consumer premium willingness, and sustained 85% participation rates demonstrate both technical feasibility and market viability. However, implementation barriers including infrastructure costs, digital literacy requirements, and governance complexity necessitate supportive ecosystems combining technological innovation with capacity building and policy support. The research contributes scalable frameworks, validated implementation strategies, and theoretical insights applicable across agricultural digitalization initiatives. As global food systems confront transparency demands, sustainability imperatives, and trust deficits, blockchain-enabled solutions offer promising pathways toward more equitable, efficient, and accountable value chains. Realizing this potential requires continued innovation adapting technologies to diverse contexts, building inclusive governance structures, and fostering collaborative ecosystems enabling shared prosperity across agricultural supply chain participants. As global food systems confront transparency demands, sustainability imperatives, and trust deficits, realizing blockchain's transformative potential globally requires practical coordinated action that are establishing international blockchain interoperability standards enabling cross-border organic certification recognition and creating subsidized infrastructure programs providing IoT sensors and connectivity to resource-constrained farmers.

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AUTHOR CONTRIBUTION STATEMENT

Chiska Nova Harsela: Conceptualization, Methodology, Investigation, Data Curation, Writing - Original Draft, Project Administration. CNH designed the research framework, developed the Hybrid Blockchain Architecture (HBA) model, conducted field implementation, managed data collection processes, and prepared the initial manuscript draft.

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