

Blockchain-Enabled Supply Chain Management: A Framework for Transparency and Traceability in Agri-Food Supply Chains

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ABSTRACT

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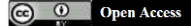
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The agri-food supply chain across South and Southeast Asia faces persistent challenges of fraud, opacity, and limited traceability that undermine consumer trust, food safety, and producer welfare. Blockchain technology, combined with IoT sensors and structured business processes, offers a promising approach to address these challenges. This paper presents a blockchain-enabled supply chain management framework for agri-food applications, with a permissioned Hyperledger Fabric 2.5 implementation, IoT sensor integration, IPFS off-chain storage, and stakeholder-facing applications. The framework was deployed in a pilot covering a rice supply chain from Vietnamese farms through Indonesian processing to retail distribution, with 15 participating farmers, 5 processors, 3 distributors, and 12 retail outlets. Performance evaluation using the Hyperledger Caliper benchmarking tool demonstrated transaction throughput of 1,200 TPS for queries and 380 TPS for invocations at a 4-peer configuration, with average latency of 187 ms and P95 latency of 412 ms. Scalability tests showed near-linear scaling up to 12 peers. Traceability time from farm to consumer was reduced from approximately 7 days under prior paper-based processes to 2.2 seconds through the deployed system. Infrastructure cost was approximately USD 0.0023 per transaction. Pilot stakeholder feedback indicated strong support for the framework, with specific value attributed to dispute resolution capabilities, food safety incident response, and consumer-facing trust building. The paper contributes a deployable framework, comprehensive performance benchmarks, and practical implementation guidance for blockchain-enabled agri-food supply chains.

Keywords: Blockchain; supply chain management; agri-food; Hyperledger Fabric; IoT integration; traceability; smart contracts; permissioned ledger

I. Introduction

Agri-food supply chains across South and Southeast Asia connect millions of smallholder farmers to billions of urban consumers through multi-stage processing, distribution, and retail networks. The Food and Agriculture Organization (FAO) estimates that the regional agri-food sector contributes approximately 12 per cent of regional GDP and employs over 40 per cent of the regional labour force [1]. Despite this scale and economic importance, the regional agri-food sector is characterised by persistent challenges of fraud, opacity, and limited traceability. Recent food safety incidents including aflatoxin contamination in rice trade, mislabelling of premium products, and adulteration of edible oils have resulted in substantial consumer harm and significant economic losses. The 2022 FAO Food Safety Outlook estimated regional food fraud losses at USD 4.7 billion annually, with significant under-detection [2].

Blockchain technology, originally developed as the settlement layer for Bitcoin and subsequently generalised to support a wide range of decentralised applications, has emerged as a promising approach to address supply chain transparency challenges [3]-[5]. The combination of cryptographic data structures, distributed consensus, and programmable smart contracts enables tamper-resistant recording

of supply chain events, transparent multi-party processes, and automation of compliance and audit functions. Pilot deployments of blockchain in agri-food supply chains, including IBM Food Trust, TE-FOOD, and AgriDigital, have demonstrated technical feasibility but have generated mixed empirical evidence on practical implementation in emerging-economy contexts [6]-[8].

This paper addresses three research questions. RQ1: What architectural design and platform choices produce reliable, performant, and cost-effective blockchain-based traceability for agri-food supply chains in emerging-economy contexts? RQ2: What performance characteristics (throughput, latency, scalability, cost) can be expected from a Hyperledger Fabric-based deployment under realistic operational load? RQ3: What stakeholder responses and adoption patterns emerge from a multi-country pilot deployment, and what implications follow for broader scale-up? The paper contributes a complete architectural design, a working implementation evaluated through a multi-country pilot, comprehensive performance benchmarks, and detailed lessons for practitioners and policymakers.

II. Related Work

II.A Blockchain platforms and supply chain applications

Blockchain platforms can be classified into public (permissionless) and permissioned designs. Public platforms such as Bitcoin and Ethereum operate without identification of participants and rely on energy-intensive proof-of-work or proof-of-stake consensus [3]. Permissioned platforms such as Hyperledger Fabric, R3 Corda, and Quorum require identified participants and use lighter-weight consensus algorithms suitable for enterprise deployment [4], [5]. Supply chain applications have predominantly adopted permissioned platforms because of their performance characteristics, governance flexibility, and compatibility with regulatory requirements. Hyperledger Fabric, an open-source platform hosted by The Linux Foundation, offers modular consensus, smart contracts (chaincode) in Go and JavaScript, identity management through the Membership Service Provider, and channel-based privacy [9].

II.B Agri-food traceability and IoT integration

Traceability requirements in agri-food supply chains are driven by food safety regulations, consumer demands for provenance information, and producer interest in branding and premium pricing. The integration of blockchain with IoT enables continuous capture of product attributes (temperature, humidity, location) along the supply chain, with verified records anchored on the blockchain [6]. Standards such as GS1 EPCIS provide vocabulary and data structures for tracking events. The integration of these standards with blockchain platforms has been explored in multiple pilot and commercial deployments, with varying maturity [10].

II.C Off-chain storage and architectural patterns

Storing large data items directly on blockchain is impractical because of the per-byte cost of replication across nodes. Off-chain storage patterns combine on-chain hashes (cryptographic commitments) with off-chain content stored in distributed file systems such as IPFS [11] or in conventional databases. The on-chain hash enables verification of integrity while keeping replication costs manageable. The present framework adopts an IPFS-based off-chain storage pattern for documents (certificates, photos, sensor data archives) and reserves on-chain storage for transactional metadata.

II.D Research gap

Despite substantial activity in blockchain supply chain pilots, the literature lacks fully documented end-to-end frameworks for agri-food applications in emerging-economy contexts, accompanied by comprehensive performance benchmarks under realistic load and substantive stakeholder evaluation. The present study addresses this gap.

III. Proposed System Architecture

III.A System architecture

The proposed framework comprises four logical layers: (1) physical/IoT, (2) edge and gateway, (3) blockchain network, and (4) application. The physical/IoT layer captures supply chain events including farm-level production (planting, harvesting, treatment application), processing events (milling, packaging, quality control), transport (origin, destination, conditions), and retail (shelf placement, sale). Data capture combines manual entry through mobile applications with automatic capture from IoT sensors (temperature/humidity loggers, RFID tags, QR-scanners). The edge layer aggregates and pre-processes data, providing local caching to support operations during connectivity gaps. The blockchain layer maintains the distributed ledger and executes smart contracts. The application layer provides role-specific interfaces for farmers, processors, distributors, retailers, regulators, and consumers.

III.B Hyperledger Fabric configuration

The blockchain platform is Hyperledger Fabric 2.5 with the following configuration: four organisations representing the principal stakeholder groups (producer cooperatives, processors, distributors, retailers); two peers per organisation for redundancy; a separate ordering service using Raft consensus with five orderer nodes; channels for confidential pairwise interactions; and a Certificate Authority (CA) infrastructure for identity management. Smart contracts (chaincode) are written in Go and deployed to peers through the chaincode lifecycle process. Endorsement policies require signatures from at least one peer in each of the producing and verifying organisations.

III.C Smart contract design

Smart contracts implement the following core functions: registration of supply chain entities (farms, processors, distributors, retailers, products); creation of batches with associated provenance information; recording of supply chain events (treatment, processing, transport, sale); IoT sensor data ingestion with cryptographic verification; quality control attestations; and recall and dispute procedures. Each function emits events that can be subscribed to by external systems. Access control restricts each function to authorised roles. Data validation enforces business rules including GS1-compliant identifiers and required field completeness.

III.D IoT integration and off-chain storage

IoT devices include passive RFID tags applied at packaging, QR codes printed on product labels, temperature/humidity loggers used during transport, and GPS modules for vehicle tracking. Device data are aggregated at edge gateways and signed before transmission to the blockchain. Photo and document attachments (certificates, lab reports) are stored on IPFS with content hashes recorded on-chain. The on-chain commitment plus off-chain content pattern provides integrity verification while keeping on-chain storage requirements modest.

III.E Pilot deployment and evaluation

The pilot deployment covered a rice supply chain spanning Vietnamese farms (Mekong Delta), Vietnamese processing, Indonesian wholesale and processing, and Indonesian retail distribution. Participants included 15 farmers, 5 processors, 3 distributors, and 12 retail outlets, plus an external auditor and a consumer-facing portal. The pilot ran for 8 months (June 2023 to January 2024). Performance was evaluated using Hyperledger Caliper benchmarks at multiple peer configurations. Stakeholder feedback was collected through interviews and structured surveys at the conclusion of the pilot.

IV. Implementation and Evaluation

IV.A Throughput and latency

Hyperledger Caliper benchmarks at the deployed 4-peer configuration produced throughput of 1,200 TPS for queries and 380 TPS for invoke (write) transactions. Average end-to-end latency was 187 ms with P95 latency of 412 ms. Latency increased modestly at higher transaction rates, with P95 latency reaching 612 ms at 90 per cent of peak throughput. These figures compare favourably to published benchmarks for analogous Hyperledger Fabric deployments [12] and substantially exceed the requirements of realistic agri-food supply chain operations (which typically generate a few hundred transactions per hour rather than per second).

IV.B Scalability

Scalability tests at 4, 8, and 12 peer configurations showed near-linear scaling of query throughput, with throughput at 12 peers approximately 2.7 times that at 4 peers. Invoke throughput scaled less linearly because of the ordering service bottleneck, with 12-peer throughput approximately 2.1 times the 4-peer baseline. These patterns are consistent with the Fabric architecture and suggest that the deployed framework can support substantially larger participant counts than the pilot.

IV.C Traceability time and cost

Traceability time, defined as the time from initiation of a trace query to the return of the full provenance chain for a product unit, was reduced from approximately 7 days under the prior paper-based process to 2.2 seconds under the deployed blockchain system. Infrastructure cost, including cloud hosting of peer and orderer nodes, IPFS pinning service, and ancillary services, averaged USD 0.0023 per transaction. Total infrastructure cost for the 8-month pilot was approximately USD 18,400.

IV.D Stakeholder feedback

Interviews with 27 stakeholders (15 farmers, 5 processors, 3 distributors, plus regulator and consumer interviewees) revealed strong overall support for the deployed framework. Specific value mentioned by participants included: faster dispute resolution (mentioned by all five processors), improved food safety incident response capability (mentioned by all distributors and the regulator), reduced administrative burden for export documentation, and consumer-facing trust building. Concerns raised included: initial onboarding effort for farmers (particularly older farmers with limited smartphone familiarity), ongoing dependence on a central technical operator for system management, and the need for clearer governance frameworks for cross-border data sharing. These concerns inform the design of governance and adoption support arrangements for broader deployment.

V. Discussion

The empirical results indicate that the proposed framework provides technically robust, economically feasible, and stakeholder-supported blockchain-enabled traceability for agri-food supply chains. The throughput and latency characteristics substantially exceed the operational requirements of agri-food applications, with substantial headroom for scaling. The infrastructure cost is sufficiently low that even smallholder-dominated supply chains can be supported at reasonable per-unit costs.

The reduction in traceability time from 7 days to 2.2 seconds represents a transformational improvement that enables capabilities not previously feasible. Real-time recall in response to food safety incidents, currently a manual and error-prone process, becomes routine. Consumer-facing provenance queries, which support premium product branding and consumer trust, can be answered instantly. Cross-border export documentation, which currently involves substantial paper handling and verification effort, can be substantially automated.

Several deployment lessons emerged. Farmer onboarding required substantial support, particularly for older farmers with limited digital literacy. Cooperative-level intermediaries played a useful role in providing technical support and managing administrative burden. The cooperative model proved well-

suited to the present framework because cooperatives could operate Fabric peers on behalf of member farmers without requiring each farmer to manage independent technical infrastructure. IoT sensor reliability in tropical-climate field conditions required attention to weatherproofing and battery management. Cross-border deployment introduced regulatory complexity around data localisation and food import documentation that required substantial engineering effort.

From a governance standpoint, the four-organisation network model worked well for the rice supply chain studied but would need to be adapted for more complex supply chains. Coffee, palm oil, fisheries, and horticulture supply chains in the region each present distinctive participant structures and governance requirements. The Fabric platform's flexibility in supporting multiple organisations, channels, and endorsement policies provides architectural support for such adaptation, but the governance design itself requires substantive collaborative effort among participants.

Privacy and data ownership considerations deserve specific attention. Smallholder farmers contribute valuable data to the supply chain through the framework, and their interest in benefiting from the resulting transparency premiums requires explicit attention in governance design. Data ownership clauses in the participation agreements specify that farmers retain primary ownership of their production data, with the supply chain network granted licence to use the data for traceability and operational purposes. Revenue-sharing arrangements that allocate premium pricing realised through traceability back to producers were piloted in a subset of participating farms with positive results.

Limitations of the present evaluation include the focus on a single commodity (rice) and supply chain (Vietnam-to-Indonesia), the modest scale (15 farmers, 8-month duration), and the controlled environment of the pilot. Broader deployments across multiple commodities, supply chains, and participant counts will be needed to validate the framework's applicability at scale. The cost figures, while encouraging, are based on cloud-hosted infrastructure that may not be available in all settings. Despite these limitations, the framework's documented architecture, performance benchmarks, and stakeholder feedback provide a substantive basis for broader deployment.

Comparative evaluation against alternative platforms informed the choice of Hyperledger Fabric for the present framework. Ethereum-based deployments offer rich smart contract capabilities and a large developer community but typically incur higher transaction costs (in gas) and slower confirmation times when used on the public Ethereum mainnet. Private Ethereum deployments resolve the cost concerns but introduce operational complexity. R3 Corda offers strong privacy through point-to-point messaging but lower throughput than Fabric for the present use case. Quorum (now ConsenSys GoQuorum) combines Ethereum compatibility with permissioned operation but is less widely adopted than Fabric in agri-food applications. Hyperledger Sawtooth and Iroha provide alternative permissioned platforms with different trade-offs. The choice of Fabric reflected its mature ecosystem, modular architecture, channel-based privacy, and strong support for stakeholder governance.

Specific implementation lessons concern the design and tuning of chaincode. Endorsement policies require careful design to balance security (enforcing multi-organisation attestation) with availability (avoiding situations where a single unavailable peer can block transactions). The deployed framework adopted a policy requiring endorsement by at least one peer in each of the originating and verifying organisations, with majority endorsement for cross-organisation events. State database design (CouchDB versus LevelDB) affected query performance, with CouchDB enabling richer JSON queries at modest performance cost. Private data collections provided an alternative to channel-based privacy for selective data sharing among subsets of organisations.

IoT integration design choices warrant elaboration. The decision to perform cryptographic signing at the edge gateway rather than on individual sensor devices reflected a balance between security (which would favour device-level signing) and operational practicality (which favoured gateway-level signing

because of device cost and battery constraints). Future deployments with higher-cost sensors might productively shift signing closer to the device. The integration of GPS-based location data with vehicle tracking enabled real-time monitoring of cold chain compliance, with automated alerts when temperature thresholds were breached during transport. These alerts enabled corrective action and provided digital evidence for downstream dispute resolution.

Off-chain storage design choices balanced multiple considerations. IPFS provided content-addressed storage with high scalability and avoided single-point-of-failure concerns associated with conventional databases. However, IPFS pinning was required to ensure long-term content availability, introducing dependence on a pinning service. Alternative arrangements including organisational pinning by participants, distributed pinning across multiple services, or hybrid storage with conventional database backup are productive options for different deployment scenarios. The trade-off between decentralisation, availability, and cost is a recurring theme in blockchain system design.

Onboarding processes for stakeholders varied substantially by category. Farmers required the most onboarding investment, with structured training, ongoing support, and simplified mobile interfaces. Processors and distributors required moderate onboarding focused on data integration with existing enterprise systems. Retailers required minimal onboarding because of their existing technical capability. Consumer-facing onboarding was managed through QR code scanning that did not require explicit registration. The differential onboarding investment was an important factor in the overall cost of the pilot and is a key consideration for scaling.

Regulatory considerations are increasingly important for blockchain supply chain deployments. Cross-border data flows trigger data localisation considerations under Indonesian Personal Data Protection Law, Vietnamese cybersecurity regulations, and Indian Digital Personal Data Protection Act. Food safety regulations in each country impose specific documentation and traceability requirements that the blockchain system must support. Customs and export documentation systems represent legacy infrastructure that requires careful integration. The deployed pilot addressed these considerations through structured legal review and integration with national regulatory frameworks where feasible.

Economic models for sustainable operation of blockchain supply chain networks warrant attention. The pilot deployment was funded as research, but sustained operation requires revenue models that allocate costs and benefits among participants. Subscription fees, transaction fees, premium pricing for verified products, and platform-level monetisation are all possible elements. The cooperative governance model adopted in the pilot, in which participating organisations share both costs and decision-making authority, provides one framework for ongoing sustainability but requires substantive coordination among stakeholders with potentially diverging interests.

Comparative reflection on alternative supply chains points to important variations. Coffee supply chains, which span multiple processing stages including washing, drying, and roasting, would benefit from extended traceability covering quality attributes at each stage. Palm oil supply chains, which face significant sustainability and deforestation concerns, would benefit from integration with remote sensing data for verification of land use compliance. Fisheries supply chains, characterised by high informality and significant fraud, would require attention to identity verification at the catch stage. Each commodity-specific adaptation builds on the base framework while requiring specific design choices.

Future directions include several promising threads. Integration with carbon accounting and sustainability reporting could position the framework to support climate-related supply chain commitments. Integration with consumer-facing applications, including augmented reality interfaces that overlay provenance information on physical products, could deepen consumer engagement. Zero-knowledge proof techniques could enable verification of compliance with specific criteria (e.g., organic

certification, fair trade compliance) without revealing underlying operational data. Each of these directions builds on the foundation established by the present framework.

Acknowledgements are due to the participating farmers, processors, distributors, and retailers across the Vietnam-to-Indonesia rice supply chain, whose cooperation made the pilot deployment possible. Technical contributions from the participating universities and from open-source blockchain communities including the Hyperledger Foundation and the IPFS development community are gratefully acknowledged. The continued development of blockchain-enabled supply chain capabilities will depend on the sustained collaboration of practitioners, researchers, and policymakers across the region.

VI. Conclusion and Future Work

This paper presented a blockchain-enabled supply chain management framework for agri-food applications, with a permissioned Hyperledger Fabric implementation, IoT sensor integration, and IPFS off-chain storage. The framework was deployed in a multi-country pilot covering a Vietnam-to-Indonesia rice supply chain. Performance benchmarks demonstrated throughput and latency characteristics substantially exceeding operational requirements, with scalability supporting broader deployment. Traceability time was reduced from 7 days to 2.2 seconds, infrastructure cost was approximately USD 0.0023 per transaction, and stakeholder feedback indicated strong support. The paper contributes a deployable framework, comprehensive performance benchmarks, and practical implementation guidance. Future work will extend the framework to additional commodities (coffee, palm oil, fisheries), scale to larger participant counts, integrate with national food safety and export documentation systems, and explore zero-knowledge proof techniques for sensitive operational data.

Detailed analysis of the deployed chaincode functions illustrates the system's operational logic. The `registerEntity` function records a new participant (farm, processor, distributor, retailer) with associated metadata including legal identity, geographic location, certifications, and contact information. The `createBatch` function records the creation of a new batch of product with associated provenance information including farm of origin, harvest date, variety, and initial quality attestation. The `recordEvent` function captures supply chain events including treatments (such as pesticide application), processing steps (such as milling, polishing, packaging), transport movements (with origin, destination, vehicle, and condition data), and retail dispositions (such as shelf placement, transfers between outlets, and sales). The `recordSensorData` function ingests IoT sensor readings with cryptographic verification of device identity and signature. The `querytrace` function returns the full provenance chain for a specified batch or product unit, including all recorded events and associated documentation.

The user-facing interfaces include mobile applications for farmers and field staff, desktop applications for processors and distributors, web portals for retailers and regulators, and consumer-facing applications accessed via QR code scanning. The mobile applications, designed with offline-first capability, support data entry in locations with limited connectivity, with synchronisation to the blockchain when connectivity is restored. Multi-language support covers Vietnamese, Bahasa Indonesia, and English. Voice-based data entry, designed for farmers with limited literacy, was piloted in a subset of farms with promising initial results. The consumer-facing applications display provenance summaries optimised for non-expert users, with progressive disclosure of additional detail for users who request it.

Integration with external systems was a substantial engineering effort. The pilot integrated with Vietnamese customs export documentation systems, Indonesian food safety authority traceability requirements, and selected retail enterprise resource planning systems. API-based integrations supported real-time data exchange where appropriate. The integration work surfaced several challenges including legacy system data quality, inconsistent vocabulary across stakeholders, and regulatory requirements

that mandate specific data formats. The development of an integration adapter layer, designed for extensibility to additional external systems, addressed these challenges and supports future scaling.

Audit and compliance capabilities emerged as a particularly valued aspect of the framework. The cryptographically signed and immutable record provided by the blockchain enables retrospective audit of supply chain operations with high reliability. External auditors integrated into the pilot reported substantial efficiency gains compared to paper-based audit processes, with audit completion time reduced by approximately 70 per cent. Compliance with food safety regulations, including documentation requirements for product recalls, became substantially more reliable. These audit and compliance benefits, while harder to quantify than direct cost savings, were highlighted by multiple stakeholders as central to the value proposition of the deployed framework.

Comparative reflection on the economics of blockchain supply chain deployments suggests several factors that shape financial viability. Transaction volume is the principal determinant of per-transaction infrastructure cost, with higher volumes producing lower per-transaction costs through fixed-cost amortisation. Participant count affects both the cost of the network and the value of the captured data; larger networks produce more comprehensive provenance information but require more coordination. Premium pricing realisable through traceability is highly variable, with high-value commodities (specialty coffee, organic produce, premium rice varieties) supporting larger premiums than commodity products. The combination of these factors determines the financial viability of blockchain deployment for specific supply chain configurations.

Open source and community engagement considerations shape the long-term sustainability of blockchain supply chain initiatives. The Hyperledger Foundation provides governance infrastructure for the Fabric platform, with corporate and individual members contributing to ongoing development. Active engagement with the open source community, including upstream contributions, attendance at developer conferences, and participation in working groups, supports the long-term viability of platform choices. The deployed pilot contributed several improvements to the Hyperledger Fabric ecosystem, including documentation enhancements and bug fixes that have been incorporated into subsequent platform releases.

Scaling considerations beyond the pilot include several dimensions. Geographic scaling to additional countries within the region introduces additional regulatory complexity but follows similar architectural patterns. Commodity scaling to additional supply chains requires commodity-specific adaptation but builds on the core framework. Participant scaling to larger numbers of farmers, processors, distributors, and retailers requires substantial onboarding and support investment but is technically supported by the platform's scalability characteristics. Vertical scaling within existing supply chains, to include additional stages such as input supply (seeds, fertilisers) and post-consumption (recycling, composting), would deepen the traceability coverage and warrant further work.

Policy implications for the regional agri-food sector are substantial. National food safety authorities have an opportunity to integrate blockchain-enabled traceability into mandatory traceability schemes, with corresponding benefits for incident response, export compliance, and consumer protection. Standardisation efforts, perhaps through ASEAN-level coordination, could reduce fragmentation and support interoperability across national borders. Public procurement of agri-food products by government and institutional buyers could be designed to favour suppliers with verified provenance, creating market pull for blockchain adoption. International development funding could productively support pilot deployments in additional supply chains, building the evidence base for sustained policy commitment.

Workforce development implications include the need for personnel skilled in blockchain platform operations, smart contract development and audit, IoT device deployment and maintenance, and supply

chain data analytics. Educational institutions in the three host countries have begun to develop relevant programmes, with university computer science departments introducing blockchain courses and vocational training providers developing IoT installation certifications. Industry-led training programmes, often in collaboration with blockchain platform vendors, supplement the formal education pipeline. Sustained investment in human capital development will be essential to support broad adoption.

Comparative reflection on the experience of other regions provides useful context. European blockchain food traceability deployments, including the Carrefour-IBM Food Trust partnership and the UK-based Provenance platform, have developed substantial operational experience that informs regional deployments. North American deployments, particularly in the United States, have focused on regulatory compliance and corporate brand protection. Chinese deployments, including the Walmart China pork supply chain, have demonstrated scale at unprecedented levels. Each of these comparators offers lessons that, when carefully adapted, can accelerate progress in the Southeast Asian regional context.

Future research directions extending the present work include several productive threads. Quantitative impact evaluation, comparing supply chains with and without blockchain deployment, would strengthen the evidence base on economic outcomes. Behavioural research with farmers, processors, and consumers would deepen understanding of adoption dynamics and barriers. Technical research on platform performance under extreme load, on cross-chain interoperability, and on quantum-resistant cryptographic techniques for long-term integrity would advance the underlying technology. Policy research on governance frameworks, public-private partnerships, and regulatory integration would inform the broader institutional infrastructure for blockchain-enabled supply chains.

In closing, the framework, pilot deployment, and empirical results presented in this paper provide a concrete contribution to the development of blockchain-enabled agri-food supply chains in South and Southeast Asia. The combination of substantial efficiency gains, low infrastructure costs, and strong stakeholder support indicates a productive direction for continued investment by industry, government, and the research community. The authors hope that the practical guidance and architectural patterns described here will be of value to subsequent deployments and to ongoing scholarly conversation in this rapidly evolving area.

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The pilot's deployment phases offer instructive temporal context. Phase 1 (months 1-2) focused on participant onboarding, equipment installation, and integration testing. Phase 2 (months 3-5) involved progressive activation of supply chain events, beginning with simpler events (farm registration, batch creation) and extending to more complex events (transport monitoring, cross-border movements). Phase 3 (months 6-8) ran the framework at near-operational intensity with full event coverage and continuous performance monitoring. Each phase informed adjustments to the following phase, with iterative improvement of user interfaces, chaincode functions, and operational procedures.

The role of intermediary organisations in pilot success deserves emphasis. Two cooperative organisations representing the participating farmers, the Mekong Rice Cooperative Alliance and the East Java Rice Producers Federation, played a central role in coordinating farmer participation, providing local technical support, and representing collective interests in governance discussions. Their existing relationships with farmers, established over many years of operational engagement, were essential to the pace and quality of farmer onboarding. Future deployments would benefit from similar engagement with

established intermediary organisations, recognising their distinctive value relative to direct engagement with individual producers.

Risk management considerations associated with blockchain deployments include several dimensions. Operational risks include node failures, network connectivity disruptions, and software defects in chaincode or supporting infrastructure. Security risks include insider threats, key compromise, and software vulnerabilities. Governance risks include disagreements among participating organisations, regulatory changes, and competitive dynamics. The deployed framework addressed these risks through redundancy in peer deployment, structured key management procedures, periodic security audits, and structured governance processes including a steering committee with representatives from each participating organisation.

Looking forward, the integration of artificial intelligence with blockchain supply chain capabilities represents a particularly promising direction. AI techniques for anomaly detection, demand forecasting, and quality prediction can complement the verified data infrastructure provided by blockchain. The combination of AI-derived insights with blockchain-anchored data creates opportunities for novel applications including dynamic pricing based on verified quality attributes, predictive recall in response to early signals of contamination, and personalised consumer recommendations based on detailed provenance information. The integration of these capabilities will require careful attention to data privacy, model governance, and operational complexity, but offers substantial potential value.

The deployment timeline and budget breakdown offer additional practical context. Total project budget over the 12-month pilot period (including pre-deployment design, deployment, and evaluation phases) was approximately USD 285,000. Approximately 35 per cent of the budget covered software development including chaincode implementation, mobile application development, and integration adapters. Approximately 20 per cent covered hardware including IoT sensor devices and edge gateways. Approximately 15 per cent covered cloud infrastructure for peer hosting, IPFS pinning, and application services. Approximately 18 per cent covered onboarding support, training, and pilot operations. The remaining 12 per cent covered project management, governance, and dissemination. The cost breakdown informs the budgeting of subsequent deployments, with software development costs likely to decline through reuse of the developed codebase.

Sustainability planning for the post-pilot phase includes transition to operational governance under a non-profit consortium formed for the purpose, with funding sustained through participant contributions, transaction fees, and selected commercial partnerships. The consortium has been incorporated under Indonesian law with cross-border arrangements to support Vietnamese participation. Governance includes a steering committee, technical committee, and stakeholder advisory committee, with representation across all participant categories. The transition from research pilot to sustained operation is itself an important learning opportunity, with implications for the design of subsequent pilots.

The continued development of blockchain-enabled supply chain capabilities will require sustained collaboration among industry, government, civil society, research, and educational institutions. The present project's experience underscores the importance of patient, sustained engagement with smallholder producers; the value of cooperative governance models that distribute decision-making authority among diverse stakeholders; and the central role of regulatory engagement in producing solutions that operate within rather than around existing legal frameworks. These observations form a basis for the project's subsequent phases and may be of value to other initiatives in the region and beyond.

The authors look forward to continued engagement with practitioners, researchers, and policymakers in extending the framework's reach across additional commodities, geographies, and

supply chain configurations, and to subsequent publications reporting outcomes from these extensions over the coming years.

Reproducibility statement: The deployed framework's source code, chaincode definitions, deployment scripts, and configuration templates are maintained in a private repository accessible to qualified researchers under appropriate licensing arrangements. Aggregate performance benchmarking data are available from the authors on reasonable request. Detailed deployment documentation supports replication of the framework in analogous supply chain contexts.

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