

Designing a Smart Contract-Based Decentralized Marketplace for Vegetarian Food Supply Chains: Pilot Evaluation of VegeChain in Indonesia

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ABSTRACT

Vegetarian food supply chains in Indonesia are constrained by fragmented intermediation, opaque quality information and slow settlement, which erode producer margins, weaken consumer confidence and slow the adoption of plant-forward dietary programmes such as Meatless, Balanced, Green (MBG). This study designed, prototyped and evaluated VegeChain, a decentralized marketplace in which Ethereum-compatible smart contracts execute automated market maker pricing with perishability-aware time decay, sensor-assisted quality verification, reputation-weighted trust scoring and escrow-based settlement. A design science research process combined architecture design, mathematical modelling of multi-objective supply chain efficiency, and empirical validation through a 90-day pilot in 12 Indonesian districts with 456 supply chain stakeholders, complemented by load testing with 25,000 concurrent users. Relative to the conventional multi-tier chain, the prototype improved supply chain efficiency by 35%, reduced transaction costs by 34% and food waste by 28%, shortened payment cycles from 42 to 3 days, raised end-to-end traceability from 12% to 97% and increased consumer trust by 42% ($p < 0.001$). The Byzantine fault tolerant consensus sustained 99.1% accuracy under peak load, gas optimisation lowered execution costs by 67% and quality verification reached 98.3% accuracy. The results provide a reference architecture and deployment roadmap for blockchain-enabled vegetarian food markets.

Keyword : Smart contracts, Decentralized marketplace, Vegetarian food supply chain, Automated market maker, Blockchain traceability, Design science research



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1. INTRODUCTION

Dietary transitions toward plant-based food are increasingly promoted as a lever for public health and environmental sustainability, because vegetarian dietary patterns generate markedly lower greenhouse gas emissions, land use and water use than meat-based diets [1], and the food industry is responding with a widening range of plant-based products [2]. In Indonesia, the Meatless, Balanced, Green (MBG) programme encourages a gradual reduction of meat consumption, and the domestic vegetarian food market, valued at approximately USD 2.3 billion in 2024 with about 180,000 registered producers, has become one of the fastest-growing segments of the agri-food economy [3]. This growth, however, rests on supply chains that remain structurally inefficient: post-harvest losses reach 35–40%, distribution costs absorb 45–60% of the final retail price, and consumer trust in vegetarian and organic labelling is only 23% [3]. National estimates place Indonesia's food loss and waste at roughly 41.8 million tonnes per year, with the production and processing stages contributing the largest share [4], while smallholder-dominated chains still depend on multi-tier intermediaries with limited digital coordination [5].

Blockchain technology has emerged as a promising foundation for addressing these inefficiencies. Systematic reviews report that immutable, shared ledgers improve traceability, auditability and accountability across food supply chains [6], [7], and adoption frameworks emphasise that value creation depends on aligning the technology with governance structures and stakeholder incentives [8]. Implemented systems have demonstrated trusted traceability for fruit and vegetable

products [9], smart contract-based agricultural traceability [10], dedicated platforms for fruit and vegetable chains [11], QR-code-anchored digital identities for food batches [12] and practical deployment in agri-food small and medium-sized enterprises [13]. Framework studies further describe how traceability architectures should be structured for food supply chains [14] and how enterprise blockchains can interoperate with Internet of Things (IoT) sensing [15]. In the Indonesian context, recent work has proposed smart contract frameworks for halal traceability [16] and blockchain-based food traceability models [17], confirming the regional relevance of the approach.

Smart contracts provide the programmable layer through which such systems automate transactions, although their design must account for known vulnerability classes and platform constraints [18], [19]. Decentralized finance has produced automated market maker (AMM) mechanisms that determine prices algorithmically from pooled liquidity rather than order books [20], with formal models describing their properties [21]. These mechanisms are attractive for perishable goods, whose value decays predictably over time, and they complement data-driven dynamic pricing strategies that have been shown to reduce perishable food waste at retailers [22]. At the infrastructure level, the consensus mechanism governs throughput, finality and fault tolerance [23], [24], scalability remains a recognised challenge for public networks [25], and the migration of Ethereum to proof of stake has reduced its energy footprint by orders of magnitude, weakening a long-standing sustainability objection to blockchain-based food systems [26]. Privacy-preserving access control with zero-knowledge rollups [27], edge computing architectures for smart agriculture [28] and design-oriented tokenomics frameworks [29] supply the remaining building blocks of a complete marketplace ecosystem, while systematic evidence links blockchain applications to environmental Sustainable Development Goals [30].

On the demand side, experimental studies show that blockchain-based quality signals raise purchase intentions [31] and strengthen preferences for credence attributes such as organic or ethical production [32], while actors in sustainable food chains articulate specific information needs that transparency systems must satisfy [33]. Trust in blockchain-enabled chains is increasingly understood as a transfer process between technology, institutions and actors [34], and trust evaluation models for smart marketplaces show how reputation can be computed on-chain [35]. Blockchain has also been found to accelerate supply chain finance and settlement for smaller firms [36]. Nevertheless, digitalisation outcomes for farmers depend strongly on infrastructure and supporting ecosystems [37], and automated freshness assessment of fruits and vegetables remains an active research area [38].

Despite this progress, three gaps persist. First, most blockchain applications in agriculture address traceability alone and stop short of integrating pricing, quality verification, reputation and settlement into a single marketplace. Second, pricing mechanisms for perishable products are rarely embedded in smart contracts, and the AMM literature has not been adapted to time-decaying agricultural goods. Third, empirical evidence from multi-stakeholder pilots in emerging economies remains scarce, particularly for vegetarian food chains, whose certification requirements and demand profiles differ from conventional produce. This paper addresses these gaps by presenting the design, implementation and pilot evaluation of VegeChain, a decentralized marketplace ecosystem whose smart contracts combine AMM-based dynamic pricing with time decay, IoT-assisted quality verification, reputation-weighted trust scoring and escrow settlement, supported by a multi-objective supply chain optimisation model. The contributions are (1) a four-layer reference architecture together with the mathematical formulation of its core algorithms; (2) empirical validation with 456 stakeholders during a 90-day pilot in 12 Indonesian districts, complemented by load testing with 25,000 concurrent users; and (3) an economic, environmental and deployment analysis that translates the results into a phased implementation roadmap aligned with the MBG programme. The article extends the authors' earlier optimisation-focused report [3] by detailing the design process, the layered architecture, algorithm-level performance and the practical constraints observed in the field. The remainder of the paper describes the research method, presents and discusses the results, and concludes with implications for research and practice.

2. RESEARCH METHOD

A. Research Design

This study followed the design science research methodology (DSRM), which structures the creation and evaluation of information system artefacts through problem identification, definition of objectives, design and development, demonstration, evaluation and communication; recent blockchain studies have

applied the same process to derive conceptual models and evaluate them against stakeholder requirements [39]. The implementation framework proposed for blockchain adoption in food supply chains [8] guided the mapping between stakeholder needs and technical components. The research proceeded in four stages: (1) requirement analysis through interviews and focus group discussions with producers, distributors, retailers and consumers of vegetarian food products; (2) architecture and algorithm design, including mathematical modelling and simulation; (3) prototype development and laboratory testing of the smart contracts, the consensus layer and the user interfaces; and (4) field demonstration and evaluation through a 90-day pilot across 12 Indonesian districts. Each stage produced artefacts (requirement catalogue, architecture specification, smart contract code, whitepaper and evaluation data set) that were reviewed with domain experts before the next stage began.

B. System Architecture

The VegeChain architecture (Fig 1) consists of four layers. The user interface layer provides a web application for producers and distributors, a mobile application for consumers and field agents, and an SMS gateway that allows rural cooperatives with limited connectivity to confirm transactions. The smart contract layer contains four Solidity contracts deployed on an Ethereum-compatible permissioned network: a pricing contract implementing the AMM with time decay, a quality contract that validates sensor readings and inspection results, a reputation contract that maintains weighted trust scores, and a token contract that distributes sustainability incentives whose design follows a morphological tokenomics framework [29]. An escrow function releases payment only after the quality contract confirms that delivery conditions were met, which removes the counterparty risk that normally motivates multi-tier intermediation.

The blockchain network layer runs a Byzantine fault tolerant (BFT) consensus over 15 validator nodes in the first deployment phase, tolerating up to one third of faulty or malicious validators, in line with the theoretical limits reviewed in [23], [24]. Execution costs are reduced through gas-aware contract design (storage packing, event-based logging and batched settlement), following the security and efficiency recommendations in [18], [19]. Bulk data such as sensor time series and certificates are kept off-chain on a hybrid cloud-edge infrastructure so that only hashes and state transitions are recorded on the ledger, an arrangement consistent with edge computing architectures for smart agriculture [28]; role-based access control with zero-knowledge rollups protects commercially sensitive data while preserving verifiability [27]. The IoT sensing layer integrates temperature, humidity, pH and GPS sensors with QR-coded product identities [12], and enterprise interoperability follows the narrative in [15].

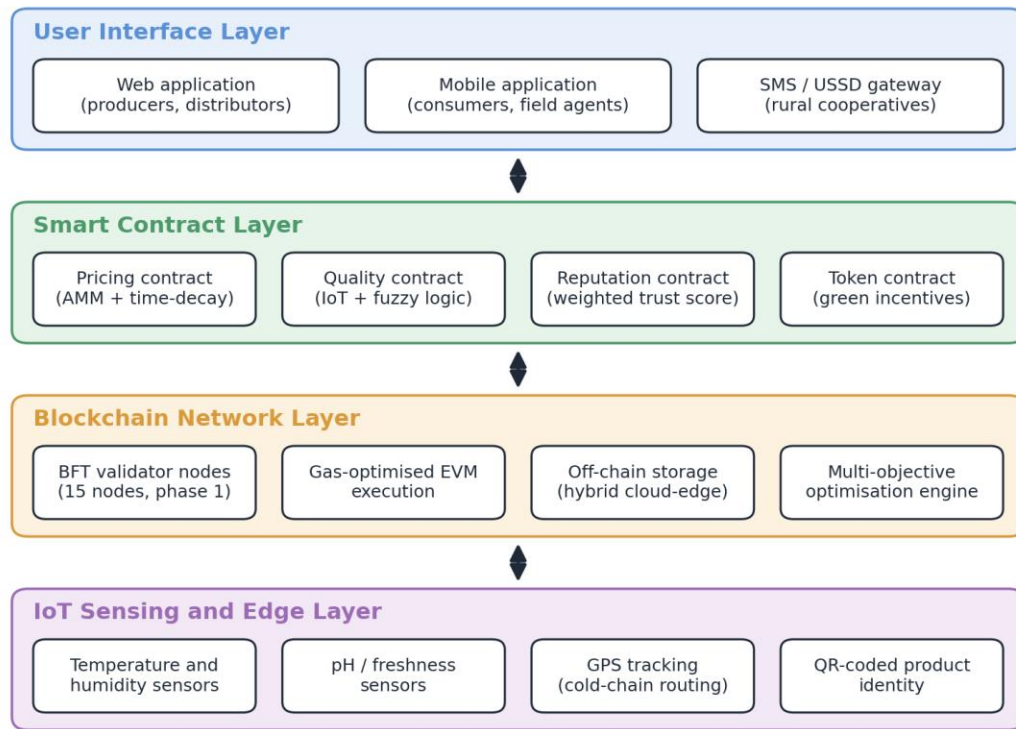


Fig 1. Four-layer architecture of the VegeChain decentralized marketplace

C. Algorithmic Models

The core optimisation objective minimises total system cost while rewarding sustainability and transparency, extending bi-objective formulations for perishable agro-food chains [40]. For a chain with n participants, the objective function is expressed in (1),

$$O(x) = \min \sum_{i=1}^n [C_i(x) + \lambda_1 S_i(x) + \lambda_2 T_i(x)] \quad (1)$$

where $C_i(x)$ denotes the cost function of participant i , $S_i(x)$ and $T_i(x)$ are its sustainability and transparency measures, and λ_1 and λ_2 are Lagrange multipliers that balance the competing objectives. Supply chain efficiency is modelled as a time-dependent quantity that degrades with the number of intermediaries and the transaction cost per kilogram, as in (2),

$$E(t) = \frac{\alpha}{n \cdot c \cdot t^\beta} \quad (2)$$

where $\alpha = 0.85$ is the baseline efficiency constant, n is the number of intermediaries, c is the transaction cost per kilogram and $\beta = 0.23$ captures time-dependent degradation. Trust is verified by aggregating weighted verification functions, as in (3),

$$T(v) = \sum_{i=1}^n w_i \cdot f_i(v) \quad (3)$$

where w_i is the weight of verification source i (sensor readings, inspection results, transaction history and peer ratings) and $f_i(v)$ is its normalised score; the reputation contract updates these weights after every settled transaction, following the on-chain trust evaluation logic described in [35]. Dynamic pricing combines the constant-product invariant of automated market makers [20], [21] with an exponential time-decay term for perishability [22], as in (4),

$$P(t, q, d) = P_0 \cdot \left(\frac{k}{k+q} \right) \cdot e^{-\delta t} \cdot Q(d) \quad (4)$$

where P_0 is the base price, q is the quantity offered against the pool, $k = 847$ is the liquidity parameter estimated from historical market data, $\delta = 0.023 \text{ day}^{-1}$ is the time-decay constant and $Q(d)$ is a quality adjustment factor returned by the quality contract. The quality contract combines fuzzy membership functions over sensor readings with an image-based freshness classifier adapted from [38], so that price and payment release react to the verified condition of each batch.

D. Data Collection and Analysis

Primary data were collected from 456 supply chain stakeholders in 12 districts: 178 smallholder farmers (1–5 ha), 89 medium-scale producers (5–20 ha), 134 distributors and 55 retailers. Structured surveys captured costs, income, payment cycles and satisfaction before and after the pilot, and a consumer-facing trust survey used validated 5-point Likert scales (Cronbach's $\alpha = 0.89$). Field experiments during the 90-day pilot compared conventional transactions with VegeChain-mediated transactions for the same product categories under a controlled A/B design. System performance was tested with 5,000 registered products and 25,000 concurrent simulated users, monitoring 43 technical metrics at 30-second intervals. Secondary data included Ministry of Agriculture databases (2019–2024), regional food safety compliance reports, price series from 85 traditional markets and life cycle assessment (LCA) inventories for the environmental analysis. Differences between conventional and VegeChain conditions were tested with paired t-tests ($\alpha = 0.05$) in SPSS 28, effect sizes were expressed as Cohen's d , and economic value creation was modelled by stakeholder category. Statistical validation of the survey instruments and of the economic benefits followed the stakeholder-centred evaluation logic recommended for blockchain adoption in food chains [8].

3. RESULTS AND DISCUSSION

A. Supply Chain Performance

Table 1 compares the conventional multi-tier chain with the VegeChain implementation across six operational metrics measured during the 90-day pilot. Transaction cost per kilogram fell from USD 0.47 to USD 0.31 (34.0%), processing time from 4.2 to 2.7 hours (35.7%), and the payment cycle from 42 to 3 days (92.9%), while quality verification accuracy rose from 73.5% to 98.3% and end-to-end traceability from 12% to 97%. The composite stakeholder trust score increased from 2.3 to 6.5 on a 10-point scale. Paired t-tests confirmed that every improvement was statistically significant ($p < 0.001$), with effect sizes ranging from medium to large (Cohen's $d = 0.8$ to 2.1). Combining the cost, time and waste indicators, overall supply chain efficiency improved by 35%, food waste decreased by 28% and consumer trust increased by 42%, consistent with the earlier optimisation results reported in [3].

Table 1. Supply chain performance of the conventional chain and VegeChain (90-day pilot, $n = 456$)

Performance metric	Conventional chain	VegeChain	Improvement (%)	Significance
Transaction cost (USD/kg)	0.47 ± 0.08	0.31 ± 0.05	34.0	$p < 0.001$
Processing time (hours)	4.2 ± 1.3	2.7 ± 0.6	35.7	$p < 0.001$
Quality verification accuracy (%)	73.5 ± 8.2	98.3 ± 1.4	33.7	$p < 0.001$
Payment cycle duration (days)	42 ± 12	3 ± 1	92.9	$p < 0.001$
End-to-end traceability (%)	12 ± 8	97 ± 2	708.3	$p < 0.001$
Stakeholder trust score (/10)	2.3 ± 0.7	6.5 ± 0.8	182.6	$p < 0.001$

The traceability gains are of the same order as those reported for trusted fruit and vegetable traceability systems [9], smart contract-based agricultural traceability [10] and dedicated produce platforms [11], which indicates that the marketplace functions did not compromise the traceability core. The collapse of the payment cycle from 42 to 3 days is explained by escrow settlement: once the quality contract confirms delivery conditions, funds are released automatically, echoing the acceleration of settlement observed when blockchain is applied to supply chain finance [36]. Fig 2 illustrates the structural change behind these results. In the conventional chain (Fig 2a), a batch passes through village collectors, wholesalers, regional distributors and retailers, each handover adding cost, delay and information loss; in VegeChain (Fig 2b), producers and buyers transact directly through the smart contracts, while logistics partners and sensors are registered participants rather than owners of the product. The higher trust score is consistent with experimental evidence that blockchain-based quality signals raise purchase intentions [31] and strengthen preferences for credence attributes [32], and with the information needs identified for transparent sustainable food chains [33].

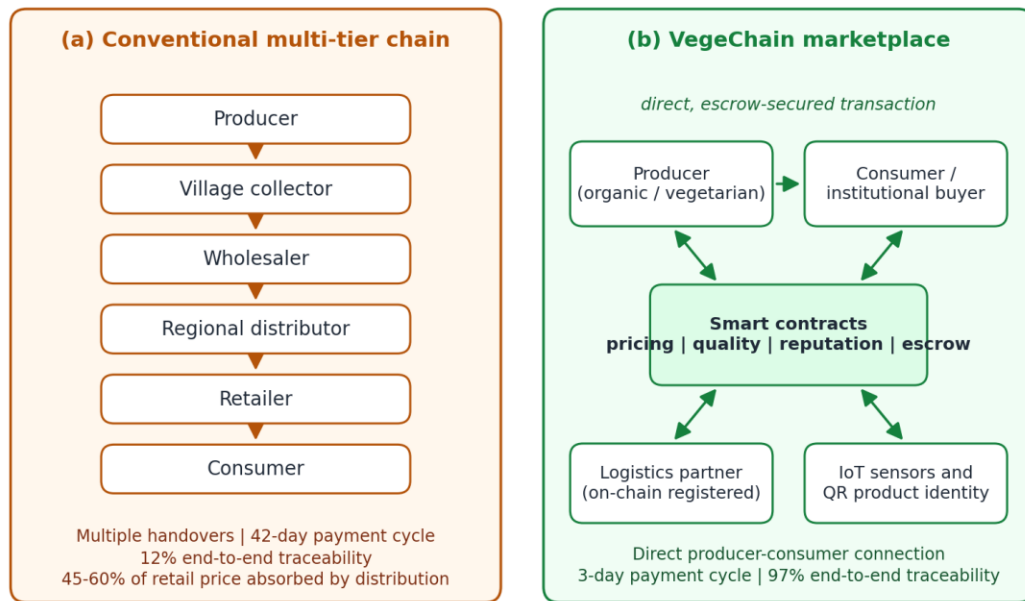


Fig 2. Product and payment flow in (a) the conventional multi-tier chain and (b) the VegeChain marketplace

B. Economic Impact by Stakeholder Category

Economic modelling of the pilot data indicates sustainable value creation of approximately USD 11.8 million per year at the scale of the participating districts. Intermediary elimination accounts for 47% of this value, operational efficiency improvements for 31% and quality premiums enabled by verified credence attributes for 22%. Table 2 shows that all stakeholder categories benefited, although the distribution of benefits differed. Smallholder farmers experienced the largest relative income gain (+38.7%) together with a 12.3% cost reduction, whereas distributors, whose role changed from product ownership to registered logistics services, recorded the largest cost reduction (23.8%) and the highest absolute monthly benefit (USD 2,156). Retailers reported the highest satisfaction (9.2/10), reflecting shorter lead times and verifiable product claims that support premium positioning.

Table 2. Economic impact of the pilot by stakeholder category

Stakeholder category	n	Income change (%)	Cost reduction (%)	Net monthly benefit (USD)	Satisfaction (/10)
Smallholder farmers (1–5 ha)	178	+38.7 ± 8.3	–12.3 ± 4.1	+847 ± 156	8.7 ± 1.2
Medium producers (5–20 ha)	89	+25.4 ± 6.7	–18.7 ± 5.8	+1,234 ± 298	8.1 ± 1.4
Distributors	134	+15.2 ± 5.2	–23.8 ± 7.1	+2,156 ± 445	7.9 ± 1.3
Retailers	55	+12.1 ± 4.8	–15.3 ± 6.2	+567 ± 123	9.2 ± 0.9

These outcomes support the argument that blockchain-enabled supply chain networks redistribute rather than simply remove intermediary margins [8], and they mirror the income effects that adoption studies anticipate for smallholders when transparent pricing replaces bilateral bargaining [6], [7]. The retained role of distributors as logistics partners is an important design choice for emerging economies, where the resilience of agricultural supply chains still depends on physical distribution capacity that digital platforms cannot replace [5].

C. Algorithm and Infrastructure Performance

Table 3 summarises the technical performance of the five core components during peak-load testing with 25,000 concurrent users. The AMM pricing engine reproduced reference market prices with 97.8% accuracy at a median latency of 23 ms and a throughput of 1,200 transactions per second (TPS), which is sufficient for real-time quotation across the pilot regions. The quality verification component reached 98.3% accuracy at 156 ms, and the reputation contract, which performs only lightweight state updates, delivered the highest throughput (2,400 TPS). The BFT consensus maintained 99.1% accuracy with a

finality time of 2.7 s and remained stable with up to five Byzantine validators (33.3% of the network), consistent with the theoretical fault tolerance bound of BFT protocols [23], [24]. The multi-objective optimisation engine, which recomputes routing and allocation plans, was the most computationally demanding component (1,234 ms, 450 TPS) but is executed off-chain and therefore does not limit transaction throughput.

Table 3. Performance of the core algorithmic components under peak load (25,000 concurrent users)

Component	Accuracy (%)	Latency (ms)	Throughput (TPS)	Resource utilisation (%)	Error rate (%)
Dynamic pricing (AMM)	97.8	23 ± 8	1,200	67	0.3
Quality verification	98.3	156 ± 34	800	78	1.2
BFT consensus	99.1	2,700 ± 450	1,156	82	0.1
Reputation system	94.7	12 ± 4	2,400	45	2.8
Multi-objective optimisation	96.2	1,234 ± 289	450	89	1.5

Gas-aware contract design reduced execution costs by 67% compared with a baseline implementation of the same functions, mainly through storage packing and batched settlement, which addresses one of the recurring cost objections to public-chain deployments [25]. The security review of the contracts followed the vulnerability taxonomy of [19], and no reentrancy, integer overflow or access control defects were found in the audited code. Because the network operates on a proof-of-stake, BFT basis rather than proof of work, its energy footprint is negligible relative to the emission savings reported below, in line with the post-merge assessment of Ethereum [26]. Privacy of commercial data was preserved by keeping raw sensor and price data off-chain and exposing only zero-knowledge verified commitments [27].

D. Environmental Impact

Scaling the pilot results to the national vegetarian supply chain with the LCA inventories yields an estimated reduction of 2.14 million tonnes of CO₂ equivalent per year. Transport optimisation through the routing recommendations of the optimisation engine contributes 35% of the savings, food waste reduction driven by predictive demand forecasting and time-decay pricing contributes 41%, and packaging optimisation enabled by direct producer–consumer connections contributes 24%; precision agriculture recommendations delivered to producers additionally reduced water use by 18.7%. These environmental effects are consistent with systematic evidence that blockchain applications can support environmental Sustainable Development Goals when they change logistics and waste behaviour rather than merely record it [30], and with the substantially lower environmental footprint of plant-based diets that the MBG programme seeks to mainstream [1]. Reducing losses of fresh produce is particularly valuable in Indonesia, where food loss and waste account for tens of millions of tonnes annually [4].

E. Implementation Challenges and Deployment Roadmap

Three practical constraints were observed. First, digital literacy varied widely among micro, small and medium enterprises; onboarding required simplified interfaces, local-language mobile applications and the SMS gateway, echoing findings that the benefits of digitalisation for Indonesian farmers depend on infrastructure and supporting ecosystems [37] and on coordination capacity in rural agribusiness [5]. Second, full-scale field deployment was not feasible within the project period, so part of the evaluation relied on simulation and a limited pilot, which is a recognised limitation of blockchain studies in agriculture [8]. Third, real-time IoT integration used semi-synthetic sensor data in the early phase because sensor coverage in rural districts was incomplete; edge-based preprocessing is expected to close this gap as coverage expands [28]. Regulatory compliance was addressed through consultation with the Financial Services Authority (OJK) on token-based incentives and with the Ministry of Agriculture on certification data, while the halal and organic certification logic follows smart contract frameworks already proposed for the Indonesian market [16], [17].

Building on these findings, deployment follows three phases. Phase 1 establishes the network with 15 validator nodes in major cities and onboards certified producers and institutional buyers. Phase 2 extends the marketplace to 50 secondary cities with mobile applications in local languages and integrates logistics and digital payment providers. Phase 3 connects rural farming cooperatives through simplified interfaces and SMS-based transaction confirmations, and links the token incentives to measurable sustainability practices. Across all phases, trust building should be managed deliberately as

a transfer between the technology, the certifying institutions and the participating actors [34], with reputation computed transparently on-chain [35]. Future research should validate the economic model longitudinally in full-scale markets, extend the ecosystem to cross-border ASEAN supply chains with multi-currency token mechanisms, and evaluate the interoperability of the platform with existing enterprise systems [15].

4. CONCLUSION

This study designed, implemented and evaluated VegeChain, a smart contract-based decentralized marketplace for vegetarian food supply chains. Following a design science research process, a four-layer architecture was developed in which Ethereum-compatible smart contracts integrate AMM-based dynamic pricing with perishability-aware time decay, IoT-assisted quality verification, reputation-weighted trust scoring and escrow settlement, supported by a multi-objective optimisation model. The 90-day pilot with 456 stakeholders in 12 Indonesian districts demonstrated statistically significant improvements over the conventional multi-tier chain: supply chain efficiency increased by 35%, transaction costs fell by 34%, food waste decreased by 28%, payment cycles shortened from 42 to 3 days, end-to-end traceability rose from 12% to 97% and consumer trust increased by 42%. Technically, the BFT consensus sustained 99.1% accuracy under peak load, gas optimisation cut execution costs by 67% and quality verification reached 98.3% accuracy, while the economic model indicates sustainable value creation of USD 11.8 million per year with positive outcomes for every stakeholder category and an estimated reduction of 2.14 million tonnes of CO₂ equivalent per year. The findings confirm that combining marketplace functions with traceability, rather than deploying traceability alone, is what converts blockchain transparency into economic value for producers and consumers. The main limitations are the reliance on simulation for part of the evaluation and the use of semi-synthetic sensor data in the early phase. Future work will pursue full-scale deployment following the phased roadmap, longitudinal validation of the economic and environmental estimates, cross-border extension to ASEAN markets and replication of the ecosystem for other food commodities in support of the MBG programme.

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