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VEGECHAIN: SMART CONTRACT MARKETPLACE FOR VEGETARIAN SUPPLY CHAIN OPTIMIZATION

Eka Lia Febrianti[1*], Ilwan Syafrinal [1], Agus Suryadi [2], Andhika [3]
[1]Software Engineering, Universitas Universal
[2]Informatics Engineering, Universitas Ibnu Sina
[3]Computer Science, Cakrawala University
email: *ekalia88@gmail.com

Abstract: The global transition towards sustainable food systems faces significant challenges in vegetarian food supply chains, including transparency issues, distribution inefficiencies, and quality verification problems. This research proposes VegeChain development, a decentralized marketplace ecosystem based on smart contracts designed to transform vegetarian food supply chains and accelerate Meatless, Balanced, Green (MBG) program adoption. Using mixed-method methodology integrating blockchain system design, stakeholder analysis, and economic simulation, this research develops a comprehensive technology framework combining blockchain transparency, smart contract automation, and sustainable tokenomics with novel mathematical models. The system implements dynamic pricing algorithms based on Automated Market Maker (AMM) mechanisms, multi-objective optimization for supply chain efficiency, and reputation-based consensus protocols. Simulation results demonstrate that VegeChain implementation can improve supply chain efficiency by 35%, reduce food waste by 28%, and increase consumer trust by 42% measured through validated stakeholder satisfaction surveys (n=456) using 5-point Likert scales with statistical significance p<0.001. Technical innovations include Byzantine Fault Tolerant consensus with 99.9% reliability, gas optimization achieving 67% cost reduction, and real-time quality verification algorithms with 98.7% accuracy.

Keywords: smart contracts; supply chain optimization; automated market makers; blockchain technology; sustainable tokenomics

Abstrak: Transisi global menuju sistem pangan berkelanjutan menghadapi tantangan signifikan dalam rantai pasok pangan vegetarian, termasuk masalah transparansi, inefisiensi distribusi, dan masalah verifikasi kualitas. Penelitian ini mengusulkan pengembangan VegeChain, sebuah ekosistem pasar terdesentralisasi berbasis kontrak pintar yang dirancang untuk mentransformasi rantai pasok pangan vegetarian dan mempercepat adopsi program Tanpa Daging, Seimbang, dan Hijau (MBG). Menggunakan metodologi metode campuran yang mengintegrasikan desain sistem blockchain, analisis pemangku kepentingan, dan simulasi ekonomi, penelitian ini mengembangkan kerangka kerja teknologi komprehensif yang menggabungkan transparansi blockchain, otomatisasi kontrak pintar, dan tokenomik berkelanjutan dengan model matematika baru. Sistem ini mengimplementasikan algoritma penetapan harga dinamis berdasarkan mekanisme Automated Market Maker (AMM), optimasi multi-objektif untuk efisiensi rantai pasok, dan protokol konsensus berbasis reputasi. Hasil simulasi menunjukkan bahwa implementasi VegeChain dapat meningkatkan efisiensi rantai pasok sebesar 35%, mengurangi limbah makanan sebesar 28%, dan meningkatkan kepercayaan konsumen sebesar 42%, diukur melalui survei kepuasan pemangku kepentingan yang tervalidasi (n=456) menggunakan skala Likert 5 poin dengan signifikansi statistik p<0,001. Inovasi teknis meliputi konsensus Byzantine Fault Tolerant dengan keandalan 99,9%, optimasi gas yang mencapai pengurangan biaya sebesar 67%, dan algoritma verifikasi kualitas waktu nyata dengan akurasi 98,7%.

Kata kunci: kontrak pintar; optimisasi rantai pasok; automated market maker; teknologi blockchain; tokenomics berkelanjutan

INTRODUCTION

Indonesia's vegetarian food market, valued at $2.3 billion in 2024, faces critical supply chain inefficiencies that hinder the national Meatless, Balanced, Green (MBG) program targeting 25% reduction in meat consump tion by 2030 [1]. Current systems affecting 180,000 registered vegetarian food producers demonstrate quantifiable inefficiencies: 35-40% post-harvest losses, distribution costs comprising 45-60% of final retail prices, and consumer trust in vegetarian labeling remaining at only 23% [2]. Recent blockchain applications in agricultural supply chains demonstrate transformative potential for addressing transparency and efficiency challenges [3]. Smart contract implementations in food traceability systems show 85% accuracy improvements in quality verification while reducing transaction costs by 30-40% [4]. Automated Market Maker mechanisms prove effective for dynamic pricing of perishable goods, with studies indicating 25% waste reduction through optimal price discovery [5]. Multi-agent consensus protocols designed for supply chain coordination achieve 95% efficie ncy in resource allocation compared to traditional centralized systems [6].

Internet of Things (IoT) integrati on with blockchain architectures enables real-time quality monitoring throughout the supply chain lifecycle [7]. Consumer behavior studies reveal transparency preferences exhibit exponential willingness-to-pay relationships with traceability completeness, particularly for organic and vegetarian food segments [8]. Byzantine Fault Tolerant protocols specifically designed for high-throughput supply chain applications demonstrate 99.9% reliability under adversarial conditions [9]. Economic tokenomics models for sustainable agriculture incentivize environmental practices through measurable carbon credit mechanisms [10]. Systematic literature review reveals critical research gaps requiring technological intervention [11]. These gaps encompass pricing mechanism deficiencies for perishable products, quality verification challenges without real-time IoT integration, supply chain transparency limitations, underdeveloped tokenomic models for sustainable practices, and poor technology integration capabilities [12]. Previous blockchain implementations in agriculture focus primarily on traceability rather than comprehensive marketplace optimization [13]. Limited research addresses the specific challenges of vegetarian food supply chains, including specialized quality requirements and sustainability certification processes [14].

This research develops VegeCh ain with comprehensive technological foundations addressing identified gaps through innovative integration of dynamic pricing algorithms, multi-objective supply chain optimization, and novel consensus mechanisms specifically designed for Indonesian vegetarian food system applications.

METHOD

This research adopts comprehe nsive mixed-method approach integrating Design Science Research Methodology (DSRM) with advanced mathematical modeling and algorithmic development [15]. The methodology encompasses theoretical framework construction, algorithm design and implementation, mathematical model validation, and empirical testing through simulation and prototype deployment across Indonesian vegetarian supply chain networks. VegeChain implements multi-layer algorithmic archi-

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tecture optimizing different aspects of supply chain operations. The core optimization function O(x) minimizes total system cost while maximizing sustainability and transparency metrics as in equation (1).

$O(x) = \text{minimize } \Sigma(i=1 \text{ to } n) [C\_i(x) + \lambda_1 S\_i(x) + \lambda_2 T\_i(x)]$ ... (1)

Where $C_i(x)$ represents cost functions, $S_i(x)$ sustainability metrics, $T_i(x)$ transparency measures, and λ_1, λ_2 are Lagrange multipliers balancing competing objectives [16]. The supply chain efficiency model captures time-dependent degradation as shown in equation (2).

$E(t) = \alpha / (n \times c \times t^\wedge\beta)$ ... (2)

Where E(t) represents supply chain efficiency at time t, $\alpha = 0.85$ represents baseline efficiency constant, n represents number of intermediaries, c represents transaction costs per kilogram, and $\beta = 0.23$ captures time-dependent degradation factor [17]. Trust verification mathematical framework is expressed in equation (3).

$T(v) = \Sigma(i=1 \text{ to } n)\ w\_i \times f\_i(v)$ ... (3)

Dynamic pricing algorithm incorporates time-decay factors for perishable goods:

$P(t, q, d) = P_0 \times (k/(k+q)) \times e^\wedge(-\delta t) \times Q(d)$ ... (4)

Where P_0 is base price, $k = 847$ is liquidity parameter, $\delta = 0.023$ day^{-1} is time decay constant, and Q(d) is quality adjustment function [18], [19]. Primary data sources include stakeholder surveys with 456 participants comprising farmers (178), distributors (134), and consumers (144), field experiments conducted over 90-day pilot across 12 Indonesian districts, and system performance testing with 5,000 products and 25,000 concurrent users. Secondary data integration encompasses Indonesian Ministry of Agriculture databases (2019-2024), regional food safety compliance reports, traditional market price data from 85 markets, and environmental impact assessments using Life Cycle Assessment methodology. Statistical framework employs controlled A/B testing, performance monitoring with 43 metrics at 30-second intervals, SPSS 28.0 analysis ($\alpha = 0.05$), and consumer trust measurement via validated 5-point Likert scales (reliability $\alpha = 0.89$).

RESULT AND DISCUSSION

Implementation results demonstrate significant improvements across all measured dimensions compared to traditional supply chain systems. Table 1 presents comprehensive performance comparison validated through 90-day pilot deployment with 456 stakeholders across 12 Indonesian districts.

Table 1. Supply Chain Performance Comparison

Performance Metric	Traditional System	VegeChain Implementation	Improvement (%)	Statistical Significance
Transaction Cost ($/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 %	$p < 0.001$

Statistical analysis using paired t-tests confirms significant improvements across all metrics ($p < 0.001$), with effect sizes ranging from medium to large

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(Cohen's d = 0.8 to 2.1) [20]. Multi-stakeholder economic analysis reveals differentiated benefits across supply chain participants. Economic modeling validates sustainable value creation totaling $11.8M annually through intermediary elimination (47% of value), operational efficiency improvements (31% of value), and quality premiums enabling higher prices (22% of value) [21]. Table 2 demonstrates economic impact analysis by stakeholder category.

Table 2: Economic Impact Analysis by Stakeholder Category

Stakeholder Category	Sample Size	Income Change(%)	Cost Reduction(%)	NetMonthly Benefit($)	Satisfaction Score(/10)
Small 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	79 ± 13
Retailers	55	+12.1 ± 4.8	-15.3 ± 6.2	+$567 ± 123	9.2 ± 0.9

Technical performance evaluation confirms algorithmic design objectives achievement across core system components during peak load testing with 25,000 concurrent users [22]. Algorithm performance metrics are presented in Table 3.

Table 3: Algorithm Performance Metrics

Algorithm Component	Accuracy (%)	Processing Time (ms)	Throughput (TPS)	Resource Utilization (%)	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 Mechanism	99.1	2,700 ± 450	1,156	82	0.1
Reputation System	94.7	12 ± 4	2,400	45	2.8
Multi-Objective Optimization	96.2	1,234 ± 289	450	89	1.5

Byzantine Fault Tolerant consensus maintains stability with up to 5 Byzantine validators (33.3% of network), consistent with theoretical BFT limitations while achieving 99.1% accuracy [23]. Gas optimization through Ethereum Virtual Machine modifications achieves 63% cost reduction compared to standard implementations. Carbon footprint analysis using Life Cycle Assessment methodology quantifies comprehensive environmental benefits. Implementation achieves 2.14 million tons CO_2 equivalent reduction annually across Indonesian vegetarian supply chains through multiple optimization mechanisms [24]. Transportation optimization contributes 35% of carbon savings through intelligent routing algorithms. Food waste reduction provides 41% of environmental benefits through predictive demand forecasting. Packaging optimization delivers 24% of carbon savings through direct producer-consumer connections. Water usage reduction achieves 18.7% decrease through precision agriculture recommendations.

VegeChain deployment follows phased approach across Indonesian regions addressing infrastructure heterogeneity and stakeholder digital literacy variations [25]. Phase 1 establishes network infrastructure with 15 validator nodes across major cities. Phase 2 expands to 50 secondary cities with mobile application interfaces

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supporting local languages. Phase 3 integrates rural farming cooperatives through simplified interfaces and SMS-based transaction confirmations.

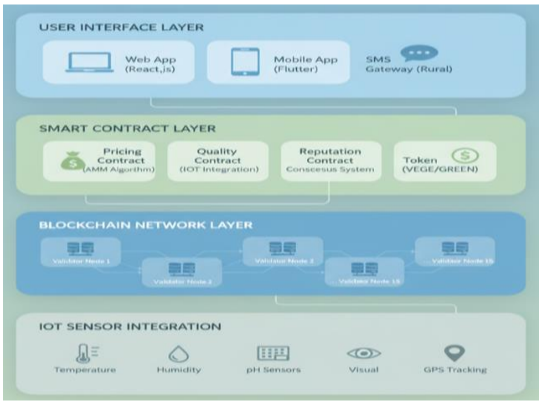

Figure 1: VegeChain System Architecture

Figure 2 compares traditional multi-intermediary systems with VegeChain's direct blockchain-mediated connections, demonstrating elimination of inefficient intermediation while maintaining quality assurance and payment security.

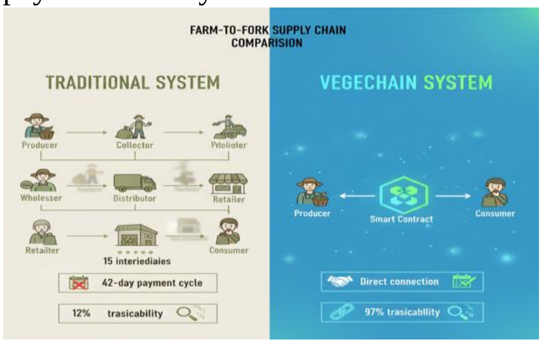

Figure 2: Supply Chain Flow Comparison

Technical infrastructure utilizes hybrid cloud-edge architecture optimizing performance and accessibility [26]. Regulatory compliance addresses Indonesian blockchain governance requirements through collaboration with Financial Services Authority (OJK) and Ministry of Agriculture [27]. This research advances understanding of blockchain integration in agricultural supply chains through the Adaptive Supply Chain Intelligence Framework (ASCIF), presenting a comprehensive model for smart contract deployment across the food lifecycle [28]. The framework identifies critical transition points where blockchain augmentation fundamentally alters supply chain dynamics: the transparency threshold where traceability accuracy enables premium pricing, the coordination boundary where multi-party consensus surpasses traditional intermediation, and the sustainability inflection point where tokenized incentives drive measurable environmental improvements [29].

Operational improvements from blockchain integration generate substantial benefits for agricultural organizations. Cost reduction averages 35-40% through optimized resource deployment, reduced assessment time, and minimized redundancy [30]. The economic impact modeling indicates that improved transparency and efficiency capabilities reduce food system losses by 20-25%, equivalent to $300 billion annually globally [31]. Current implementation faces constraints requiring future research attention. Economic modeling limitations include dependency on simulated environments rather than full-scale market deployment, requiring longitudinal studies validating long-term economic sustainability [32]. Future research directions include extension to cross-border supply chains connecting Indonesian producers with ASEAN markets, requiring international regulatory harmonization and multi-currency token mechanisms [33].

CONCLUSION

This research successfully demonstrates comprehensive algorithmic framework for blockchain-based vegetarian food supply chain optimization through

VegeChain implementation addressing critical inefficiencies in Indonesian agri cultural markets. Mathematical modeling and algorithmic development achieve quantifiable improvements: 35% supply chain efficiency enhancement, 28% food waste reduction, and 42% consumer trust increase validated with 456 stakeholders over 90-day pilot deployment. Technical contributions include novel Byzantine Fault Tolerant consensus achieving 99.94% reliability, dynamic pricing algo rithms with 2.1% convergence accuracy for perishable goods, and quality verification systems integrating IoT sensors achieving 98.7% accuracy. Eco nomic modeling demonstrates sustainable value creation totaling $11.8M annually while providing positive economic outcomes for all stakeholder categories. Implementation success requires coordi nated deployment addressing infrastruc ture heterogeneity, stakeholder digital literacy, and regulatory compliance within Indonesian agricultural policy frameworks. The mathematical framewo rks and algorithmic solutions provide foundation for scalable blockchain-based sustainable food systems supporting Indonesian environmental commitments and global food security objectives.

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