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INTEGRATION OF BLOCKCHAIN AND IoT IN THE FERTILIZER SUPPLY CHAIN: KAIZEN FRAMEWORK FOR TRANSPARENCY AND SUSTAINABILITY IN INDONESIA'S RICE PRODUCTION CENTERS

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ABSTRACT. The fertilizer supply chain servicing Indonesian agroindustrial production encounters persistent systemic inefficiencies. Lack of transparency and poor cargo traceability across complex maritime logistics networks severely impair the sustaining capacity of agricultural systems. Digitalization offers profound strategic solutions to tackle these structural weaknesses. This study evaluates the integration of Blockchain and Internet of Things (IoT) technologies within a Kaizen continuous improvement framework to enhance the performance of agro-input distribution. The research employs a quantitative methodology utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM). The authors gathered primary empirical data from a purposive sample of 150 practitioners operating within the transportation and maritime logistics sector. Analytical findings confirm that integrating distributed ledgers with real-time sensor monitoring significantly amplifies supply chain transparency and accountability. The structural model yielded a robust explanatory coefficient proving that technological deployment directly optimizes logistical sustainability. A key contribution of this research highlights the insufficiency of digital infrastructure without institutional capacity building. The Kaizen philosophy functions as an essential mediator that empowers logistics stakeholders to iteratively adopt digital tracking mechanisms. The study concludes that combining hardware, software, and continuous human improvement creates a resilient logistical architecture capable of securing national fertilizer distribution. Future empirical validation expanding to end-point farmers remains highly recommended.

INTRODUCTION

The distribution of critical agricultural inputs across the Indonesian archipelago presents a significant logistical challenge. As a maritime nation, the sustainability of its agroindustrial sector depends heavily on highly efficient sea freight and regional transportation networks. Unfortunately, the current fertilizer supply chain is hindered by profound structural inefficiencies, ranging from severe distribution bottlenecks to a pervasive lack of transparency regarding cargo origin and handling quality (Martina *et al.*, 2024). These systemic vulnerabilities disrupt the timely availability of inputs, ultimately threatening broader agricultural stability at the local production level (Ibrahim, 2023). Integrating advanced ledger technologies offers a pathway to stabilize this system and align the agricultural sector with sustainable circular economy practices (Pakseresht *et al.*, 2022). Moving physical goods across complex maritime routes requires a significant overhaul of traditional supply chain management. Digitalization serves as a highly strategic intervention to address these logistical hurdles. The implementation of advanced digital infrastructure provides the visibility necessary to track physical materials seamlessly from

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upstream maritime distributors to downstream rural nodes (Hasan *et al*., 2024; Keefe *et al*., 2024). Similar traceability applications combining blockchain and Internet of Things (IoT) have already demonstrated significant success in specialized agricultural sectors, such as ensuring origin authenticity in the olive oil supply chain (Vitaskos *et al*., 2024).

Transitioning the sector toward Agri-Food 4.0 requires robust technological convergence (Cantorani *et al*., 2025). This convergence increasingly involves securing the industrial Internet of Things to protect sensitive supply chain data across wide logistical networks (Halder *et al*., 2025). Traditional centralized databases used by logistics providers are notoriously vulnerable to data silos and unauthorized manipulation, which hinders cross-sector collaboration (Mane *et al*., 2024). By integrating blockchain architecture with the IoT, maritime logistics operators and agro-input distributors can establish an unprecedented level of trust and operational control (Hasan *et al*., 2023). This integration presents profound opportunities for precision agriculture, despite the technical challenges inherent in its deployment (Torky and Hassanein, 2020). Blockchain provides a decentralized, tamper-proof ledger that secures transactional data and validates product authenticity across a vast supply network (Morchid *et al*., 2023; Rushchitskaya *et al*., 2024). Simultaneously, IoT sensor arrays actively monitor the physical parameters and geographical movement of cargo during transit. This real-time oversight minimizes delays and protects the physical integrity of sensitive agricultural commodities (Pullo *et al*., 2023; Siddique *et al*., 2025). When deployed together, these tools eliminate information asymmetry and build a highly resilient logistics framework capable of adapting to logistical shocks (Amentae and Gebresenbet, 2021). Building resilience is especially crucial for maintaining food and agricultural supply chains during unforeseen natural or systemic disruptions (Mandal *et al*., 2023). The immutable record-keeping enabled by smart contracts ensures strict adherence to regulatory standards while preventing fraudulent mislabeling or illicit diversion of subsidized fertilizers during sea and land transit (Sugandh *et al*., 2023; Jiang *et al.,* 2024).

Academic discourse heavily supports the performance gains of digital synergy within supply networks. Blockchain and IoT directly optimize resource allocation, lower operational costs, and fortify the supply chain against external disruptions (Sridhar *et al*., 2023; Pratiningrum, 2025). Overcoming the inherent implementation challenges of these innovations is critical for modernizing supply chain management (Kumar *et al*., 2025). High-value logistics channels increasingly rely on these digital mechanisms to execute automated verifications and secure border procedures efficiently (Sundram, 2023; Chiaraluce *et al*., 2024). Empirical studies have validated that immutable ledgers dramatically elevate systemic accountability and transparent data sharing among otherwise fragmented supply chain stakeholders (Ellahi *et al*., 2024; Vern *et al*., 2024; Hassoun *et al*., 2022). Deploying sophisticated algorithms in traditional distribution environments is not a frictionless process. Significant structural and cultural barriers persist, particularly concerning infrastructure readiness and user capability in developing regional logistics hubs (Keefe *et al*., 2024). Advanced tracking systems alone cannot rectify systemic logistical failures if the human actors managing sea freight and distribution channels resist adoption or lack the necessary digital literacy.

This operational friction highlights a critical empirical gap in the current supply chain literature. Successful technological integration requires more than just deploying sensors and cryptographic ledgers; it demands an adaptive organizational management philosophy (Taufiq *et al*., 2024). This study introduces the Kaizen framework as a fundamental sociotechnical mediator. Kaizen emphasizes continuous incremental improvement, empowering logistics actors to systematically refine their digital workflows rather than face disruptive technological mandates. Real-time data collection through IoT devices allows local distributors to adjust their resource management iteratively and objectively (Musyaffa *et al*., 2023; Sa'adah *et al*., 2025). Through participatory evaluation and constant feedback loops, transportation stakeholders can optimize distribution routes, monitor cargo conditions, and maintain data integrity with greater consistency (Dhal and Kar, 2024; Duan *et al*., 2024). Ultimately, this study proposes a structured, Kaizen-driven model for integrating blockchain and IoT within the Indonesian fertilizer logistics network. By actively evaluating the perceptions of transportation and logistics service users, this study aims to demonstrate how digital tracing and continuous improvement collectively enhance transparency, operational sustainability, and proactive risk mitigation across complex agroindustrial supply chains (Husain *et al*., 2025; Charlebois *et al*., 2024).

RESEARCH AND MATERIALS

Research Framework and Operational Context

This study adopts a quantitative approach employing Partial Least Squares Structural Equation Modeling (PLS-SEM) to evaluate the structural relationships between digital technology integration and sustainable logistics performance. The primary context of this research revolves around the maritime transportation and logistics sector, which functions as a critical distribution artery for Indonesia's agroindustrial supply chains. The necessity for robust logistics networks to transport essential agricultural inputs across the archipelago is reflected in the rapid growth of the national transportation sector. Official data from the Central Bureau of Statistics indicate a consistent expansion of logistics enterprises operating within the country, detailing a continuous growth trajectory even amidst global disruptions. As detailed in Table 1, the growth trend of logistics and transportation enterprises shows a steady increase from a pre-pandemic baseline of 13,500 units in 2019 to a projected 16,200 units by 2024. This sustained sectoral growth underscores the operational urgency of integrating advanced data governance frameworks within expanding logistics networks.

This sustained sectoral growth underscores the operational urgency of integrating advanced data governance frameworks within expanding logistics networks. As the volume of agro-input shipments increases, transportation operators face mounting pressure to guarantee cargo integrity and optimize distribution turnaround time. Consequently, this study operationalizes the Kaizen philosophy alongside technological parameters to assess how continuous improvement cultures mediate digital adoption among logistics practitioners.

Sampling Strategy and Data Collection

This study employed a purposive sampling strategy targeting active users and managerial practitioners within the maritime freight and agro-logistics transportation sectors. A total of 150 valid respondents participated in the primary data collection. These individuals possess direct operational experience in navigating complex distribution routes and utilizing digital tracking mechanisms for cargo management. Data were acquired using a structured questionnaire distributed through digital channels. The instrument employed a standard Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) to quantify respondents' perceptions regarding technology deployment and its subsequent operational impact. The chosen sample size satisfies the fundamental statistical threshold required for PLS-SEM path analysis, ensuring sufficient statistical power to validate the proposed structural model.

Analytical Flowchart and Methodological Process

To systematically address the research objectives, the analytical progression followed a strict and sequential framework. The evaluation began with theoretical conceptualization and moved directly to empirical validation using the SmartPLS software suite. A visual representation of this methodological sequence is depicted in the flowchart below.

The evaluation began with theoretical conceptualization and moved directly to empirical validation using the SmartPLS software suite. A visual representation of this methodological sequence is depicted in the flowchart below, as shown in Figure 1, which outlines the comprehensive step-by-step process from research initiation to strategic logistics formulation.

Table 1. Growth trend of logistics and transportation enterprises in indonesia

Year	Number of Enterprises (Units)	Contextual Description
2019	13,500	Pre-pandemic baseline estimation
2020	14,200	Initial e-commerce and digital distribution surge
2021	14,900	Post-pandemic operational recovery
2022	15,300	Strategic logistics sector expansion
2023	15,800	Verified structural data (BPS)
2024	16,200	Projected trajectory based on historical BPS trends

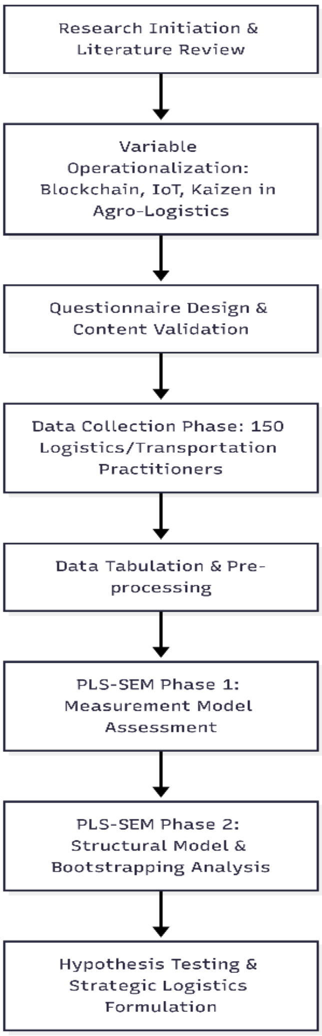

Figure 1. Research Method

The PLS-SEM methodology involves a two-stage evaluation. The measurement model was subjected to rigorous testing to establish indicator reliability, convergent validity, and discriminant validity. Once the measurement metrics surpassed the established academic thresholds, the analysis proceeded to the structural model evaluation. The second phase utilized a bootstrapping resampling technique to generate T-statistics and P-values, which definitively confirmed or rejected the hypothesized causal pathways between digital integration and supply chain sustainability.

Variable Operationalization Matrix

A critical component of this methodology is the precise definition of empirical indicators. The structural model incorporates independent variables representing technological inputs, a mediating variable representing the management framework, and dependent variables capturing the resulting logistical performance. To align the theoretical constructs with the practical realities of the agroindustrial logistics sector, the measurement indicators were calibrated to reflect cargo management, tracking transparency, and transit efficiency. These constructs and their specific operational indicators are systematically outlined in Table 2, providing a clear matrix of the independent, dependent, moderating, and intervening variables used in this study. A critical component of this methodology is the precise definition of empirical indicators.

Table 2. Operational variable

Variable Category	Construct	Operational Indicators
Independent Variable (X1)	Technology Integration	Sensor Deployment Density, Telemetry Accuracy, Maritime Network Connectivity, Ledger Immutability, Decentralized Logistics Control, Cargo Origin Traceability
Independent Variable (X2)	Kaizen Framework	Continuous Improvement Culture, PDCA Logistics Integration, Stakeholder Capacity Building
Dependent Variable (Y1)	Supply Chain Transparency	Shipment Origin Visibility, Transit Cost Clarity, Stakeholder Data Accessibility
Dependent Variable (Y2)	Logistics Sustainability	Administrative Cost Reduction, Cargo Waste Reduction, Cargo Quality Assurance, Logistics Trust Building, Input Safety Traceability
Moderating Variable (Z)	Boundary Conditions	Regulatory Support, Digital Port Infrastructure, Digital Literacy of Transporters, Implementation Costs
Intervening Variable (V)	Functional Mechanisms	Data Transmission Velocity, Automated Smart Contract Processing

Table 2 presents the empirical foundation for the statistical analysis. By linking abstract digital concepts, such as distributed ledgers, directly to tangible logistics outcomes, such as cargo quality assurance and administrative cost reduction, the research design provides a highly robust mechanism for evaluating structural supply chain transformation.

RESULTS AND DISCUSSIONS

The operationalization of the integrated technological framework yielded quantitative outputs that strongly validated the structural hypotheses proposed for the maritime agro-logistics sector. Gathering data from 150 active transportation practitioners provided a robust empirical foundation for understanding how digital traceability directly alters supply chain dynamics. The findings were systematically categorized into foundational statistical overviews, structural equation modeling outcomes, and specific technological integration metrics. These data points collectively illustrate the systemic transformation occurring within agricultural input distribution networks.

Basic Statistical Overview and Correlation Analysis

The initial phase of the quantitative analysis evaluated the foundational relationship between the adopted digital interventions and the key logistics performance indicators. The empirical data strictly delineate exceptionally high correlation coefficients across fundamental operational variables within the agroindustrial transportation sector. The application of distributed ledger technologies in conjunction with sensor networks directly correlates with elevated systemic performance.

As systematically quantified in Table 3, metrics concerning transactional security and verifiable traceability of cargo origin demonstrated the most pronounced statistical alignments. This initial matrix serves as a quantitative baseline, confirming that the deployment of digital traceability infrastructure inherently corresponds with augmented data governance. The convergence of IoT mechanisms for real-time environmental tracking ensures that these statistical gains are based on continuous and immutable data aggregation (Adewusi *et al.,* 2023).

Table 3. Correlation analysis of technological integration and supply chain indicators

Variable Code	Operational Indicator	Correlation Coefficient (r)	Statistical Significance (p-value)
X1.1	Transaction Security	0.87	< 0.01
X1.2	Cargo Origin Traceability	0.91	< 0.01
X1.5	Distribution Traceability	0.9	< 0.01
X2.2	Logistics Automation	0.85	< 0.05
X2.3	Cargo Quality Monitoring	0.88	< 0.01
Y2.1	Overall Supply Chain Transparency	0.91	< 0.01
Y5.1	Systemic Accountability	0.89	< 0.01

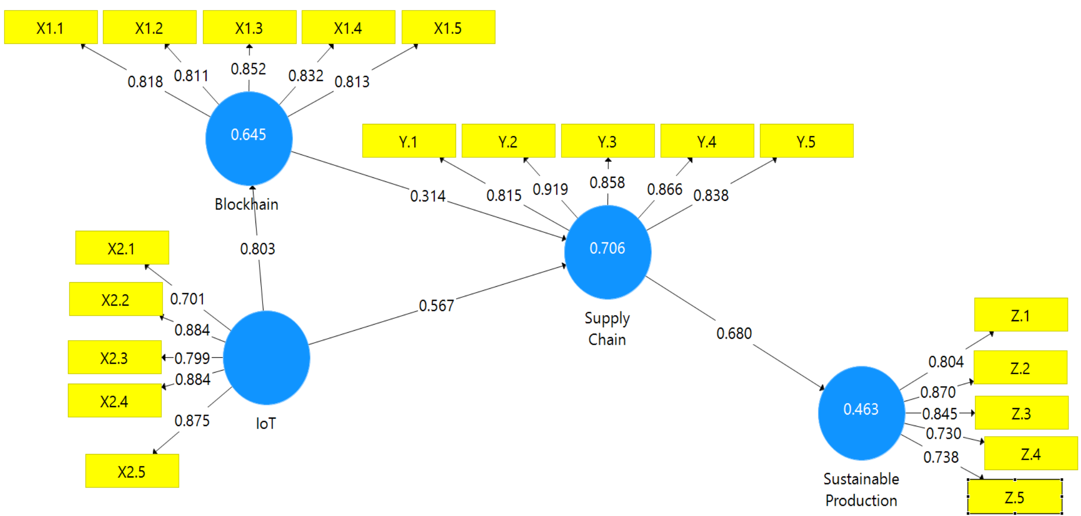

Figure 2. Multilayered causal framework of blockchain, IoT, and kaizen integration

Structural Framework Outcomes and Path Analysis

Following the rigorous validation of the measurement metrics, the structural pathways were analyzed using SmartPLS to determine the exact predictive capability and explanatory power of the model.

Structural mapping revealed that the combination of blockchain architectures and IoT sensor networks accounts for a substantial proportion of the variance within the supply chain framework. This complex interplay is comprehensively visualized in Figure 2, which illustrates the multilayered causal framework of blockchain, IoT, and Kaizen integration within the structural model. The model achieved a highly significant explanatory coefficient (R-squared) of 0.706. The directional path coefficients highlight nuanced technological dynamics. The deployment of IoT systems has a stronger direct influence on logistics efficacy, with a recorded path coefficient of 0.567. The blockchain integration vector recorded a coefficient of 0.314. Despite this variance in the intensity of the direct impact, both interconnected systems remain critical for structural transformation. This integrated supply chain framework subsequently exerts a formidable positive influence on the ultimate sustainable distribution outcomes by registering a robust structural coefficient of 0.680.

Hypothesis Testing and Statistical Significance

To conclusively validate the proposed theoretical pathways and transition from observational correlation to statistical certainty, a rigorous bootstrapping procedure was performed. This resampling technique extracted the necessary significance metrics to verify the generalizability of the findings across the broader maritime logistics population.

The computational outcomes presented in Table 4 confirm beyond a reasonable doubt that all hypothesized relationships within the framework are statistically significant. The structural interaction between IoT implementation and supply chain enhancement generated a highly significant statistical value of 5.815. This substantially exceeds the standard baseline threshold for acceptance. The specific relationship connecting the overarching supply chain framework to sustainable agroindustrial production proved exceptionally robust and yielded a statistical metric of 9.241. Even the secondary pathway connecting blockchain infrastructure to supply chain transparency recorded a significant value of 3.135. These definitive hypothesis-testing results authenticate the systemic logistical advantages of embedding advanced digital architectures within the fertilizer distribution sector.

The Symmetrical Necessity of Hardware and Software Integration

The structural evaluation delineates a profound symmetry in how distributed ledger architectures and sensor networks contribute to overarching logistics governance. From a practical perspective, capturing granular agronomic logistics data through advanced IoT sensors is operationally futile if the underlying data transmission channels are susceptible to manipulation. The immutable cryptographic security provided by a blockchain network is fundamentally useless if the initial cargo data entered into the system are inaccurate at the source. The identical structural dependencies observed in the model suggest that true systemic transformation within transportation networks relies on a dual-pronged approach. The hardware functions as the objective sensory organ of the supply chain, whereas the software acts as an incorruptible central nervous system. This synergistic dependency aligns perfectly with contemporary international logistics theories postulating that achieving absolute zero-trust traceability requires both physical and digital authentication of goods and informational records, respectively (Ganguly *et al.*, 2023; Taufiq *et al.*, 2024).

Overcoming Structural Information Asymmetry in Fertilizer Distribution

The exceptionally robust validation metrics concerning cargo origin transparency indicate a critical paradigm shift in resolving chronic, localized bottlenecks. Historically, Indonesian distribution networks have been heavily fragmented and characterized by profound information silos, where data regarding shipping schedules and inventory levels are hoarded by centralized intermediaries.

Table 4. Bootstrapping results and hypothesis testing validation

Structural Pathway	Path Coefficient	T-Statistic	P-Value	Conclusion
Blockchain -> Supply Chain	0.314	3.135	0	Supported
IoT -> Supply Chain	0.567	5.815	0	Supported
Supply Chain -> Sustainable Production	0.68	9.241	0	Supported

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This asymmetry inevitably breeds logistical inefficiencies and creates vulnerabilities to systemic leakages. The deployment of a decentralized ledger disrupts this opaque operational model by democratizing data access. When every transition of cargo ownership and geographical movement is autonomously logged by smart contracts, the opportunity for fraudulent mislabeling is systematically eliminated. The empirical outcomes demonstrate that digitized traceability directly translates into elevated systemic accountability. Enforcing stringent visibility protocols empowers local distribution cooperatives and national regulatory bodies to conduct instant audits (Panwar *et al*., 2023).

Mediating Constraints and the Imperative of the Kaizen Philosophy

While the technological core of the proposed framework exhibits formidable theoretical validity, the velocity of digital transformation is heavily contingent on specific socio-technical boundary conditions. Deploying sophisticated algorithms is insufficient without corresponding institutional capacity building in the logistics sector. Abrupt and radical technological mandates frequently encounter severe resistance from transportation practitioners. This vulnerability underscores the absolute strategic necessity of integrating the Kaizen continuous improvement philosophy into the deployment architecture. Rather than imposing a rigid digital ecosystem on traditional maritime and land transportation communities, the Kaizen approach facilitates iterative evolution. Prioritizing systematic feedback loops and continuous user training ensures that technological interventions remain culturally congruent. Analytical validation proves that long-term sustainability in logistics digitalization is not solely a computational challenge. It is a complex organizational management endeavor that requires resilient policy support and continuous stakeholder empowerment to optimize the distribution of critical agricultural inputs (Keefe *et al*., 2024; Vern *et al*., 2024).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The fusion of distributed ledgers and sensor networks transcends mere technological upgrades in agroindustrial logistics. It functions as a fundamental restructuring of supply chain governance. This study establishes that embedding the Kaizen philosophy acts as the critical catalyst required to transform rigid digital tools into adaptable socio-technical systems for maritime and land transportation practitioners. Therefore, policymakers and logistics operators must prioritize institutional capacity building alongside physical infrastructure investments to successfully secure the national fertilizer distribution network against external disruptions. The digital transition within this sector relies entirely on empowering human actors to manage transit routes.

The empirical boundaries of this study are currently confined to mid-stream supply chain operators. Consequently, the localized perspectives of endpoint agricultural users remain unknown. Future investigations should pivot toward rural cooperative managers and field-level farmers to comprehensively validate the end-to-end efficacy of the proposed digital framework. Expanding this structural model to accommodate high-value perishable food commodities represents another vital trajectory for subsequent academic inquiry to further strengthen the national food security mechanisms.

Recommendations

To successfully operationalize and sustain this technological framework, several strategic directives must be executed. Initially, government bodies and private sector entities must prioritize strengthening digital infrastructure to ensure stable Internet connectivity and reliable IoT device deployment across remote agricultural zones. This infrastructural enhancement must be immediately followed by comprehensive training initiatives designed to elevate the digital literacy of farmers and supply chain actors regarding blockchain utilization and precision agriculture. Furthermore, establishing a resilient technology-driven ecosystem requires active multisectoral collaboration encompassing academic institutions, agritech startups, and localized farmer cooperatives. Finally, policymakers must construct adaptive regulatory standards concerning data protection and product certification, complemented by a continuous socioeconomic evaluation system to systematically monitor the environmental and commercial impacts of this digital transformation.

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