

การบูรณาการ IOT บล็อกเชน และ AI เพื่อเพิ่มความสามารถในการตรวจสอบย้อนกลับและสมรรถนะ
การปฏิบัติการในห่วงโซ่อุปทานอาหาร: การทบทวนวรรณกรรมอย่างเป็นระบบ
และการวิเคราะห์ตามกรอบ TOE ในประเทศไทย

IOT, Blockchain, and AI Integration for Enhanced Traceability and Operational
Performance in Food Supply Chains: A Systematic Review and
TOE Framework Analysis in Thailand

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Received: September 30, 2025

Revised: December 10, 2025

Accepted: December 13, 2025

บทคัดย่อ

ห่วงโซ่อุปทานอาหารกำลังเผชิญกับแรงกดดันจากสถานการณ์ด้านความปลอดภัย การทุจริตอาหาร และความไว้วางใจ ทำให้การตรวจสอบย้อนกลับเป็นสิ่งที่จำเป็นในการเพิ่มความสามารถในแข่งขัน เนื่องจากการพึ่งพาเทคโนโลยีดิจิทัลเพียงชนิดเดียวยังคงมีข้อจำกัด ดังนั้น การบูรณาการระบบอินเทอร์เน็ตของสรรพสิ่ง (IoT) บล็อกเชน (Blockchain) และปัญญาประดิษฐ์ (AI) ร่วมกัน เพื่อให้เกิดความโปร่งใสตลอดโซ่อุปทาน ข้อมูลเชื่อถือได้ และสามารถคาดการณ์ได้ทันเวลา จึงมีความสำคัญอย่างยิ่งสำหรับประเทศไทย ซึ่งเป็นผู้ส่งออกสินค้าเกษตรและอาหารรายสำคัญ อย่างไรก็ตาม การยอมรับการใช้เทคโนโลยีดิจิทัลเหล่านี้ในกลุ่มผู้ประกอบการขนาดกลางและขนาดย่อมยังไม่มากนัก เนื่องจากเงินทุน ทักษะ และโครงสร้างพื้นฐานดิจิทัลที่ยังไม่ทั่วถึง งานทบทวนวรรณกรรมอย่างเป็นระบบนี้ยึดแนวทาง PRISMA เพื่อสังเคราะห์ผลงานวิจัยที่ผ่านการพิจารณาล้นกรองระหว่างปีพ.ศ. 2562-2568 ที่เป็นการบูรณาการทั้งสามเทคโนโลยี ในบริบทห่วงโซ่อุปทานอาหาร พร้อมใช้กรอบแนวคิดเทคโนโลยี-องค์กร-สิ่งแวดล้อม (TOE) วิเคราะห์ปัจจัยสนับสนุนและอุปสรรคของประเทศไทย ผลการสังเคราะห์แสดงให้เห็นว่า การบูรณาการเทคโนโลยีช่วยส่งเสริมขีดความสามารถด้านการตรวจสอบย้อนกลับ ได้แก่ การมองเห็นข้อมูลแบบเรียลไทม์จากระบบอินเทอร์เน็ตของสรรพสิ่ง การบันทึกที่ตรวจสอบได้และแก้ไขไม่ได้ด้วยระบบบล็อกเชน และการยืนยันแหล่งที่มาด้วยการวิเคราะห์ของระบบปัญญาประดิษฐ์ที่ส่งผลกับสมรรถนะการปฏิบัติการที่จับต้องได้ ไม่ว่าจะเป็นการตัดสินใจและการเรียกคืนสินค้าที่รวดเร็วขึ้น การควบคุมคุณภาพที่แม่นยำขึ้น และการลดต้นทุน ในบริบทประเทศไทย ปัจจัยสนับสนุนคือนโยบายภาครัฐ มาตรฐานอุตสาหกรรม และความร่วมมือระหว่างภาคส่วน ส่วนอุปสรรคสำคัญคือเงินทุน โครงสร้างพื้นฐานที่ไม่เสมอภาค ช่องว่างด้านทักษะ และกฎระเบียบ โดยเฉพาะกับผู้ประกอบการรายย่อย โดยสรุป งานทบทวนวรรณกรรมนี้เสนอกรอบแนวคิดที่นำการตรวจสอบย้อนกลับเป็นตัวแปรคั่นกลางเชื่อมโยงการบูรณาการเทคโนโลยีกับสมรรถนะการปฏิบัติการด้านความเร็ว คุณภาพ และต้นทุน พร้อมข้อเสนอเชิงนโยบายเพื่อยกระดับอุตสาหกรรมอาหารไทยในยุคดิจิทัล

คำสำคัญ: ระบบอินเทอร์เน็ตของสรรพสิ่ง, ระบบบล็อกเชน, ระบบปัญญาประดิษฐ์, ความสามารถในการตรวจสอบย้อนกลับ, ห่วงโซ่อุปทานอาหาร

Abstract

Food safety incidents, food fraud, and increasing trust deficits are exerting pressure on food supply chains, thereby necessitating robust traceability capabilities as a competitive advantage. Relying on a single digital technology remains insufficient in scope. Therefore, the integration of the Internet of Things (IoT), Blockchain, and Artificial Intelligence (AI) is critically important for Thailand as a major agro-food exporter to achieve comprehensive supply chain transparency, reliable data, and timely predictive insights. However, adoption rates among small and medium-sized enterprises (SMEs) remain modest due to high costs, skills gaps, and inadequate digital infrastructure coverage. This systematic literature review employs PRISMA-guided procedures to synthesize both quantitative and qualitative peer-reviewed studies published between 2019 to 2025, examining the integrated application of all three technologies, including pairwise combinations, within food supply chain contexts. It utilizes the Technology–Organization–Environment (TOE) framework to analyze Thailand-specific enablers and barriers and to interpret the connections between enhanced traceability capabilities and measurable operational performance outcomes. The synthesis reveals that technology integration strengthens traceability through three core pillars: real-time data visibility from IoT sensing and tracking systems, tamper-resistant and verifiable records through blockchain, and provenance verification through AI analytics and pattern recognition. These elements collectively translate into tangible operational benefits, including expedited decision-making and product recall processes, more precise and efficient quality control mechanisms, and cost reductions through automation, waste minimization, and comprehensive risk management. Within the Thai context, key enablers include government policy support, established industry standards, and multi-stakeholder collaborative frameworks, while significant barriers encompass high initial investment requirements, uneven digital infrastructure distribution, skill development gaps, and regulatory compliance burdens—particularly challenging for small-scale operators. In conclusion, this review proposes a conceptual framework positioning traceability as a mediating mechanism linking technology integration with operational performance improvements in speed, quality, and cost reduction dimensions, and provides actionable policy recommendations regarding infrastructure investment and capability enhancement initiatives to accelerate the responsible and inclusive advancement of Thailand’s food industry in the digital era.

Keywords: Internet of Things (IoT), Blockchain, Artificial Intelligence (AI), Traceability, Food supply chain

1. Introduction

Complex food supply chains face critical challenges: contamination risks require rapid source identification and recalls (Zhou et al., 2022), fraud demands rigorous authentication (Stranieri et al., 2021), and consumer trust relies on transparent quality assurances (Zhou et al., 2022). Effective traceability systems have thus become essential for industry competitiveness and reliability.

Digital technologies, particularly the Internet of Things (IoT), Blockchain, and Artificial Intelligence (AI), offer powerful tools for enhancing food supply chain processes. IoT devices collect real-time data,

Blockchain ensures secure, immutable record-keeping, and AI delivers advanced analytics to optimize traceability. Recent studies by Talpur et al. (2023) and Vilas-Boas et al. (2023) highlight the growing trend of integrating these technologies to achieve more comprehensive solutions than any single technology can provide. While these three technologies offer individual benefits, their combined integration creates synergistic effects that enhance traceability capabilities beyond what any single or paired combination can achieve. The integration of all three technologies enables comprehensive traceability systems that simultaneously address transparency, data integrity, and intelligent decision-making throughout the supply chain.

Although research on IoT, Blockchain, and AI individually is extensive, there is a notable gap in systematic literature reviews examining the combined impact of all three technologies on traceability and operational performance. For example, Zhou et al. (2022) investigate traceability enhancements but do not assess quality, speed, or cost dimensions, nor do they consider the full integration of IoT, Blockchain, and AI. Tsolakis et al. (2023) evaluate AI and Blockchain integration in Thailand's tuna-industry supply chain, showing improved transparency but omitting IoT and a systematic analysis of operational outcomes. Moreover, barriers and enablers specific to the Thai context have yet to be thoroughly synthesized.

Thailand occupies a significant position in global agri-food exports, yet it still faces food safety and quality challenges that force exporters to meet increasingly stringent international standards (Holzapfel & Hampel-Milagrosa, 2020). Adoption of advanced digital tools remains limited among smallholder farmers and small and medium-sized enterprises (SMEs), primarily due to high costs, technical skills, and uneven infrastructure (Yooyativong & Kamyod, 2023).

The Technology-Organization-Environment framework, or TOE, is widely used to understand how organizations adopt new technologies (Bryan & Zuva, 2021). It considers three important areas: technology, organization, and environment (Baker, 2011). This approach is valuable for food supply chains because adopting integrated technologies like IoT, Blockchain, and AI requires coordinating across technological capabilities, organizational structures, and regulatory environments simultaneously. For Thailand's food industry, where many small and medium-sized enterprises face limited digital infrastructure, budget constraints, and unclear regulations (Yooyativong & Kamyod, 2023), the TOE framework helps identify enablers and barriers to technology adoption. This structured perspective is essential for developing practical recommendations that address all three dimensions together.

To fill these gaps, this article conducts a PRISMA-guided Systematic Literature Review and applies the Technology-Organization-Environment (TOE) framework to achieve three objectives: 1) To examine how integrating IoT, Blockchain, and AI enhances traceability capabilities in food supply chains; 2) To analyze how improved traceability drives operational performance gains in speed, quality, and cost; and 3) To identify the critical barriers and enablers for implementing such integrated technologies in Thailand's food industry. The findings will contribute a synthesized theoretical framework and offer practical guidance for entrepreneurs and government agencies to strengthen Thailand's food-sector competitiveness.

2. Materials and methods

2.1 Research Design

This study employs the Systematic Literature Review (SLR) as the primary tool for gathering, selecting, and analyzing data. This method is appropriate for addressing research objectives that require synthesizing a large body of research (Tranfield et al., 2003).

2.2 Search Strategy

2.2.1 Database

This review uses Scopus exclusively for its PRISMA-guided systematic literature review and for the TOE framework analysis because of its extensive, high-quality coverage. Searches in TCI and Google Scholar informed the background context but are not part of the SLR process or included in Figure 1.

2.2.2 Search String

To ensure comprehensive literature coverage and the ability to analyze research related to technology integration, the search strategy is designed for flexibility. Search terms are tailored to focus on articles discussing the integration of at least two technological systems within the context of food supply chains and traceability. The search comprises three groups, as follows:

2.2.2.1 Integration of Blockchain and IoT

Search string: TITLE-ABS-KEY(("Blockchain" AND ("Internet of Things" OR "IoT")) AND ("Traceability" OR "Transparency") AND ("Food Supply Chain" OR "Agricultural Supply Chain" OR "agri-food" OR "agri-product" OR (("Food" OR "Agriculture") AND "Supply Chain")))

2.2.2.2 Integration of Blockchain and AI

Search string: TITLE-ABS-KEY(("Blockchain" AND ("Artificial Intelligence" OR "AI" OR "Machine Learning")) AND ("Traceability" OR "Transparency") AND ("Food Supply Chain" OR "Agricultural Supply Chain" OR "agri-food" OR "agri-product" OR (("Food" OR "Agriculture") AND "Supply Chain")))

2.2.2.3 Integration of IoT and AI

Search string: TITLE-ABS-KEY(("Internet of Things" OR "IoT") AND ("Artificial Intelligence" OR "AI" OR "Machine Learning")) AND ("Traceability" OR "Transparency") AND ("Food Supply Chain" OR "Agricultural Supply Chain" OR "agri-food" OR "agri-product" OR (("Food" OR "Agriculture") AND "Supply Chain")))

Articles obtained from search groups 2.2.2.1-2.2.2.3 will be combined, and duplicate records will be removed to prepare the data in accordance with PRISMA principles for the subsequent selection process.

2.3 Search Scope

There are four criteria defining the search scope within the Scopus database: 1) Articles published in peer-reviewed academic journals. 2) Studies in English. 3) Articles published from 2019 to 2025. 4) Full-text articles accessible for comprehensive review.

2.4 Screening and Selection Process

Articles were screened and selected following PRISMA guidelines. To ensure the reliability and validity of the synthesized data, a rigorous quality assessment was integrated into the selection process.

2.4.1 Inclusion Criteria

The main inclusion criteria were: 1) peer-reviewed academic articles (excluding conference abstracts and articles in press without full data); 2) published in English; 3) studies examining the integration of IoT, Blockchain, and AI, including pairwise combinations that contribute to a holistic traceability framework; 4) conducted within food or agricultural supply chain contexts; and 5) presenting measurable outcomes relevant to traceability capabilities or operational performance.

2.4.2 Exclusion Criteria

The main exclusion criteria were as follows: 1) non-research articles (e.g., reviews, editorials, book chapters); 2) studies limited to the application of a single digital technology without synergistic integration; 3) articles with inaccessible full texts; and 4) articles identified as retracted or lacking rigorous methodological standards during the quality assessment phase.

The screening process and the number of articles will be summarized in the PRISMA flow diagram for the systematic literature review as shown in Figure 1.

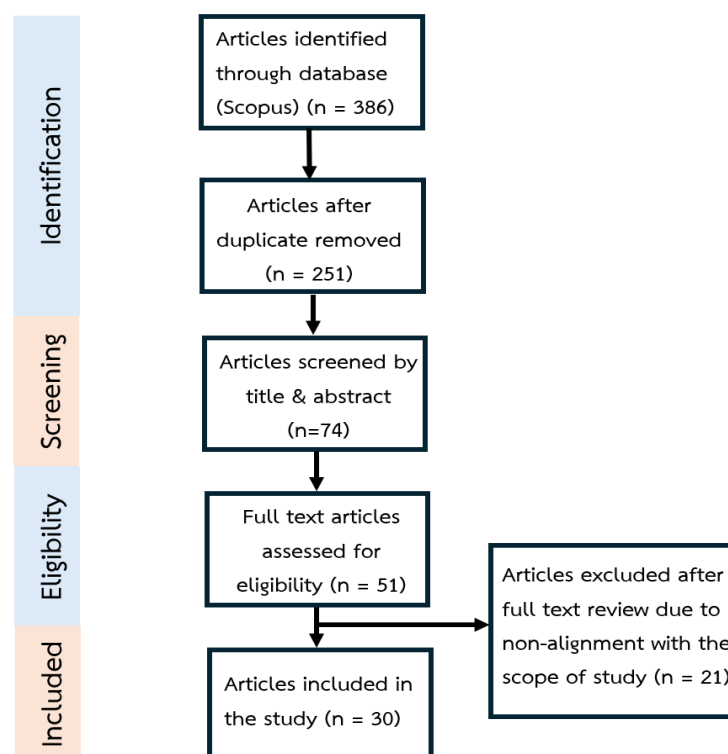


Figure 1. PRISMA Flow Diagram for Systematic Literature Review

Note: Figure 1 shows only the PRISMA flow for the systematic literature review based on Scopus. Additional TCI and Google Scholar searches supported contextual analysis but are excluded here.

2.5 Data Extraction and Analysis

Data extracted from each study comprised the author, publication year, research methodology, technology type (IoT, Blockchain, AI), implementation context, outcomes, and success factors. A standardized extraction form ensured consistency and minimized bias in data collection. The study also examined factors supporting and hindering technology integration in Thailand's food supply chain through the Technology-Organization-Environment (TOE) framework, a widely accepted model for understanding technology adoption (Bryan & Zuva, 2021). According to Baker (2011), the TOE framework classifies adoption influences into three contexts: technological, which covers existing systems, technology complexity, and compatibility with current infrastructure; organizational, which includes organizational size, resource availability, structural characteristics, and management support; and environmental, which involves industry structure, competitive pressure, and regulatory requirements. Extracted data were systematically coded by these dimensions to reveal patterns, trends, and barriers, enabling a thorough, structured analysis of technology adoption in food supply chains.

The synthesis process adopted an integrative approach, combining findings from pairwise-technology studies (such as IoT integrated with Blockchain) with triple-technology studies. Instead of separating them into distinct analysis layers, evidence was mapped to specific functional pillars, Transparency, Security, and Provenance, to demonstrate how these technologies act as complementary components of a unified digital ecosystem.

3. Results

3.1 Thematic Synthesis of Findings

3.1.1 Three Pillars of Enhanced Traceability

By synthesizing insights from both pairwise combinations and fully integrated models, the synergistic impact of IoT, Blockchain, and AI becomes evident across three core traceability pillars:

3.1.1.1 Transparency and visibility: The integration of IoT, Blockchain, and AI enhances transparency and visibility by enabling continuous, real-time monitoring of product location and condition through IoT sensors, with records stored on a shared, tamper-resistant blockchain ledger (Liberty et al., 2025; Rossi et al., 2025). AI analytics further process these data streams to generate alerts, forecasts, and decision-support dashboards, allowing stakeholders to identify disruptions and potential bottlenecks before they escalate (Vilas-Boas et al., 2023).

3.1.1.2 Data Integrity and Security: Data integrity and security are strengthened when granular observations from IoT devices are preserved as immutable blockchain transactions, reducing opportunities for unauthorized modification or data loss (Rossi et al., 2025). AI models operate as an additional validation layer by detecting anomalous patterns, sensor errors, or suspicious activities, thereby filtering out unreliable inputs and reinforcing trust in the recorded information (Femimol & Joseph, 2025; Zhang et al., 2023).

3.1.1.3 Provenance and Authenticity: Provenance and authenticity are reinforced by combining IoT-based tracking of each processing and logistics step with blockchain's verifiable chain of custody (Monteiro et al., 2021; Liu et al., 2025). AI techniques then authenticate origins and specific claims, such as geographical indication or Halal status, through pattern recognition and advanced classification methods, enabling the reliable differentiation of genuine products from counterfeits (Yang et al., 2025; Nawaz et al., 2025)

These three pillars collectively provide the conceptual foundation for examining how integrated IoT, Blockchain, and AI adoption translates into measurable improvements in speed, quality, and cost dimensions in subsequent sections.

3.1.2 Relationship Between Traceability Capabilities and Operational Performance

Technological integration does not merely enhance traceability capabilities; it translates these capabilities into tangible operational advantages. The synthesis of prior literature reveals that the synergistic collaboration of IoT, Blockchain, and AI drives measurable improvements across three strategic dimensions: speed, quality, and cost reduction. The following sections examine these impacts in detail.

3.1.2.1 Speed

Speed enhancement is the first critical dimension in which technology integration transforms operations. By combining real-time IoT data, immutable blockchain records, and AI-driven analytics, organizations accelerate responsiveness across three levels: 1) decision-making, 2) production cycles, and 3) risk management. The quantitative impact of these improvements is summarized in Table 1.

Analysis of Speed Outcomes:

1) Data Access and Decision-Making

Real-time visibility allows for instant stakeholder action. Studies indicate that animal health issues can be detected 24 hours in advance (Serrano-Torres et al., 2025), with alerts issued within 5 seconds, reducing overall response time by 30% (Halder et al., 2025). Platform efficiency is also notable, with user data requests fulfilled in just 2-5 milliseconds (Shahbazi & Byun, 2021).

2) Production and Quality Control

Automated systems leverage data integrity to operate with speed and precision. Image-based quality assessments take merely 5–60 milliseconds per unit (Femimol & Joseph, 2025; Yin et al., 2025), while pathogen identification occurs between 20 seconds and 15 minutes (Yang et al., 2025). Furthermore, blockchain transactions are verified in approximately 15 seconds (Femimol & Joseph, 2025), minimizing administrative delays.

3) Risk Management and Product Recall

Provenance capabilities drastically improve crisis response. The IBM-Walmart case demonstrates that blockchain reduces traceability lead time from 7 days to 2.2 seconds (Liberty et al., 2025; Tao et al., 2023). Additionally, AI-driven risk prediction is 80% faster than traditional methods, enabling preemptive risk mitigation (Liberty et al., 2025).

Table 1. Quantitative Metrics on Speed Enhancement from Technology Integration

Category	Context/Examples	Key Performance Indicators (KPIs)	Quantitative Outcomes	Reference
1. Data Access and Decision Making	AI sensors for animal health alerts.	Response Time /Early Detection	30% reduction in response time; alerts within 5 seconds; detection 24 hours in advance.	Halder et al. (2025); Serrano-Torres et al. (2025)
	Blockchain platform retrieval.	System Response Time	Data requests answered in 2–5 milliseconds.	Shahbazi and Byun (2021)
2. Production and Quality Control	AI Computer Vision for sorting/inspection.	Processing Time per Unit	Processing completed in 5–60 milliseconds/unit.	Femimol & Joseph (2025); Yin et al. (2025)
	Biotech sensors for pathogens.	Detection Time	Anomaly detection in 20 seconds (contaminants) to 15 minutes (pathogens).	Yang et al. (2025); Liberty et al. (2025)
	Blockchain transactions.	Processing Time	Transaction processing time in 15 seconds.	Femimol & Joseph (2025)
3. Risk Management and Product Recall	Blockchain traceability (IBM-Walmart)	Traceability Time	Lead time reduced from 7 days to 2.2 seconds.	Liberty et al. (2025); Tao et al. (2023); Ellahi et al. (2023)
	AI risk prediction	Processing Speed	Prediction accelerated by 80%; risk-event processing in 30 seconds.	Liberty et al. (2025); Femimol and Joseph (2025)

Note: This table synthesizes evidence of accelerated supply chain processes. Key insights indicate response times drop by up to 30%, and blockchain-enabled traceability reduces recall lead times from days to seconds, facilitating a shift from reactive to proactive management.

3.1.2.2 Quality

Quality assurance constitutes the second critical performance dimension. Integrated technology strengthens quality through multiple mechanisms, shifting the focus from reactive testing to proactive prevention. The combination of AI precision, IoT monitoring, and Blockchain verification enhances capabilities in: 1) operational quality control, 2) proactive quality management, and 3) fraud prevention. The measurable impacts of these enhancements are presented in Table 2.

Analysis of Quality Outcomes:

1) Operational Quality Control

Data integrity forms the cornerstone of high production standards. Reliable data inputs, secured by anomaly detection with up to 96% precision (Zhang et al., 2023), enable AI systems to operate at peak efficiency. Multiple studies confirm that this data foundation allows automated

classification and sorting systems to achieve accuracy rates between 84% and 98.7% (Frikha et al., 2023; Bhat et al., 2025; Yin et al., 2025).

2) Proactive Quality Management

Real-time visibility transforms quality management from inspection to prediction. Research demonstrates that IoT and AI can forecast spoilage or bacterial contamination with 85–95% accuracy (Chandran et al., 2025; Hassoun, 2025). Additionally, intelligent packaging systems leverage this data to improve the accuracy of shelf-life monitoring by 25% (Liberty et al., 2025), ensuring fresher products reach the consumer.

3) Safety Assurance and Fraud Prevention

Provenance capabilities serve as a powerful tool for consumer protection. Advanced AI techniques identify origins, adulteration, or specific certifications (such as Halal) with accuracy exceeding 94% (Liu et al., 2025; Nawaz et al., 2025). This rigorous verification leads to tangible safety outcomes, including a 30% reduction in safety incidents (Kanwal et al., 2025) and an 85% reduction in product counterfeiting (Rajan & Wani, 2025).

Table 2. Quantitative Metrics on Quality from Technology Integration

Category	Context/Examples	Key Performance Indicators (KPIs)	Quantitative Outcomes	Reference
1. Operational Quality Control	AI and Machine Learning for classification and sorting.	Classification/Detection Accuracy	High accuracy ranging from 84% to 98.7% across diverse contexts.	Frikha et al. (2023); Bhat et al. (2025); Jiang et al. (2025); Yin et al. (2025)
	Sensor data filtering.	Data Filtering Accuracy	96% precision in anomaly detection.	Zhang et al. (2023)
	Blockchain data verification	Data Accuracy	Data integrity maintained at 92%, with only a 3% error rate.	Femimol and Joseph (2025)
2. Proactive Quality Management	IoT and AI for spoilage prediction	Prediction Accuracy	Spoilage and contamination with 85%–95% accuracy.	Chandran et al. (2025); Hassoun (2025)
	Smart packaging to monitor shelf life	Monitoring Accuracy	Shelf-life monitoring accuracy improved by 25%.	Liberty et al. (2025)
3. Safety Assurance and Fraud Prevention	AI for adulteration/origin ID (e.g., Halal)	Identification Accuracy	Accuracy exceeding 94%, approaching nearly 100%.	Liu et al. (2025); Nawaz et al. (2025); El-tahlawy et al. (2025)
	Traceability systems.	Incident/Forgery Reduction	Safety incidents reduced by 30%; food fraud curtailed by up to 85%.	Kanwal et al. (2025); Rajan and Wani (2025)

Note: This table presents empirical evidence of quality improvements. Key insights demonstrate that AI-driven detection achieves high accuracy (up to 98.7%), while integrated systems significantly reduce food safety incidents by 30% and fraud by up to 85%.

3.1.2.3 Cost Reduction

Cost reduction is the third key performance dimension influenced by integrated IoT, Blockchain, and AI adoption in food supply chains. The literature indicates that these technologies lower costs through three main mechanisms: reducing product loss and food waste, decreasing operational and transaction costs, and mitigating risks and damage-related losses. The empirical evidence for these mechanisms is summarized in Table 3.

Analysis of Cost Reduction Outcomes:

1) Product Loss and Food Waste

Transparency and visibility capabilities enable real-time monitoring of product status and demand, shifting management from problem-solving to problem prevention. Empirical literature demonstrates that this proactive approach reduces food waste and losses by 14% to 65% (Hassoun, 2025; Kanwal et al., 2025). Furthermore, it decreases spoilage of perishable products by 20 to 30% (Liberty et al., 2025) and minimizes overstock issues by up to 25% (Sun et al., 2025).

2) Operational and Transactional Costs

Data integrity ensures that automated processes run on trusted information. When systems verify data security, smart contracts can execute transactions without human intervention. This automation directly impacts the bottom line, with research confirming overall operational cost reductions of 15% to over 23% (Kanwal et al., 2025; Sridhar et al., 2023). Specific input costs also drop significantly, including an 80% reduction in pesticide use (Liberty et al., 2025) and a 25% cut in energy consumption (Yin et al., 2025).

3) Minimizing Costs from Risks and Damages

Provenance and authenticity serve as critical risk management tools. By enabling complete traceability through immutable records, technology directly combats food fraud—a risk causing USD 10-15 billion in annual global damage. Additionally, authentic source identification limits the scope of product recalls, potentially decreasing overall supply chain damage by up to 20% (Bhat et al., 2025; Sun et al., 2025).

Table 3. Quantitative Metrics on Cost Reduction from Technology Integration.

Category	Context/Examples	Key Performance Indicators (KPIs)	Quantitative Outcomes	Reference
1. Product Loss and Food Waste	IoT and AI demand forecast (e.g. catering, aviation)	Food Waste/Loss Reduction	Decreases ranging from 14% to 65%	Hassoun (2025); Kanwal et al. (2025)
	IoT and digital twin technology for cold-chain monitoring of perishables.	Spoilage/Product Loss Reduction	Decreases of 20% to 30%	Liberty et al. (2025)
	Blockchain-based data management for improved forecasting.	Overstock Reduction	Reduction of 25%.	Sun et al. (2025)
2. Operational and Transaction Costs	Integrating digital technologies into manufacturing and agricultural.	Overall Operational Cost Reduction	Decreases ranging from 15% to over 23%.	Kanwal et al. (2025); Sridhar et al. (2023)
	AI-driven computer vision for precision agriculture.	Raw Material/Pesticide Cost Reduction	Reduction of 80% in pesticide costs.	Liberty et al. (2025)
	AI for environmental control in smart greenhouses.	Energy Cost Reduction	Reduction of 25% in energy costs.	Yin et al. (2025)
3. Risks and Damages-Related Costs	Technology to minimize system losses and prevent fraud.	Damage/Fraud Loss Reduction	Around 20% reduction in system damage; contributes to mitigating food-fraud losses valued at USD 10–15 billion per year.	Bhat et al. (2025); Sun et al. (2025)

Note: This table summarizes reported cost savings from integrated digital technologies. Key findings show substantial reductions in food waste (up to 65%), operational costs (up to 23%), and risk-related losses, providing a strong economic rationale for technology adoption in food supply chains.

3.2 Barriers and Enablers of Technology Adoption

The literature reveals that integrating emerging technologies into food supply chains encounters various barriers and benefits from multiple enabling factors. These factors can be classified according to the Technology–Organization–Environment (TOE) framework, as summarized in Table 4.

Table 4. Summary of Barriers and Enablers Arising from Technology Integration.

TOE	Factors	Types	Explanation	Reference
1. Technology	High investment cost	Barrier	High initial expenditures for installing, maintaining, and operating advanced technologies (such as blockchain, AI, and IoT), as well as associated data storage and analytics costs.	Dhal & Kar (2025); Hassoun (2025); Hassoun et al. (2023); Issa et al. (2024); Kanwal et al. (2025); Liberty et al. (2025); Qiao et al. (2024); Rajan & Wani (2025); Rossi et al. (2025); Singh et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Technological complexity	Barrier	Operation and maintenance require specialized knowledge and expertise, and certain AI models function as “black boxes,” making them difficult to understand and interpret.	Rossi et al. (2025); Singh et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Integration Standards	Barrier	The absence of unified integration standards, both technical and regulatory, hinders compatibility among diverse systems and platforms across supply chain organizations.	Liberty et al. (2025); Monteiro et al. (2021); Rossi et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Data security and privacy	Barrier	Concerns about safeguarding data against cyberattacks and leaks, as well as protecting business and consumer data privacy.	Dhal & Kar (2025); Issa et al. (2024); Liberty et al. (2025); Rossi et al. (2025); Sun et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Scalability & Infrastructure	Barrier	Lack of fundamental infrastructure, such as high-speed internet, to support system operations.	Hassoun (2025); Hassoun et al. (2023); Qiao et al. (2024); Rajan and Wani (2025); Sun et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
2.Organization	Organizational & Personnel Constraints	Barrier	Budget and resource constraints coupled with a shortage of personnel possessing the necessary skills, knowledge, and awareness to leverage new technologies, particularly within SMEs.	Čapla et al. (2025); Dhal & Kar (2025); Ellahi et al. (2025); Kanwal et al. (2025); Rajput et al. (2025); Singh et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Top Management Support	Enabler	Vision and commitment of top management serve as critical drivers for resource allocation, fostering change, and cultivating an organizational culture receptive to new technologies.	Bhat et al. (2025); Liberty et al. (2025)

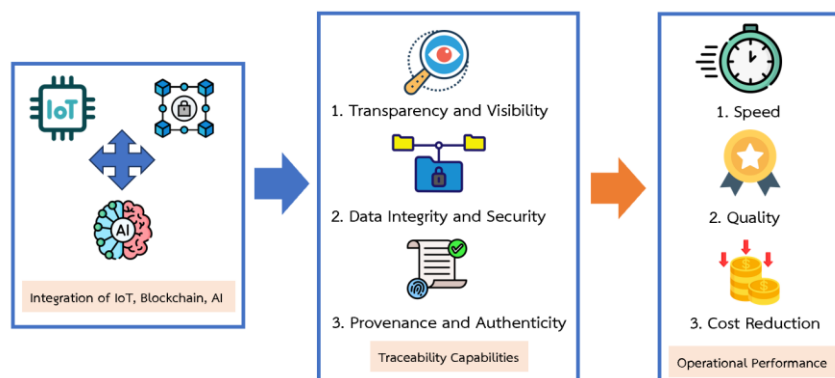
Table 4. Summary of Barriers and Enablers Arising from Technology Integration (Cont.).

TOE	Factors	Types	Explanation	Reference
3.Environment	Market Acceptance & Pressure	Enabler/ Barrier	Consumer demand for transparency serves as a significant driving force, whereas consumers' willingness to pay continues to pose a notable barrier.	Bhat et al. (2025); Rajan & Wani (2025); Rossi et al. (2025)
	Regulation & Government Policy	Enabler/ Barrier	Strict safety regulations and government incentive policies are key enablers, but the absence of clear laws for new technologies remains a barrier.	Čapla et al. (2025); Hassoun, 2025; Liberty et al. (2025); Rajan & Wani (2025); Rajput et al. (2025); Sunmola et al. (2025); Yin et al. (2025)
	Supply Chain Collaboration	Enabler	Effective implementation depends on collaboration, the sharing of reliable data, and support from supply chain partners.	Ellahi et al. (2025); Issa et al. (2024); Kanwal et al. (2025); Rossi et al. (2025); Sridhar et al. (2023); Yin et al. (2025)

From the table above, these factors constitute a crucial conceptual framework for discussing the challenges and opportunities in the Thai context in the following chapter.

4. Discussion

The results in Table 4 confirm that technology integration enhances traceability capabilities by delivering transparent, accurate data and verifiable provenance. This mechanism improves operational performance by accelerating processes, elevating quality, and generating tangible cost reductions across food supply chains, as illustrated in the diagram below:

**Figure 2.** Technology Integration for Enhanced Traceability and Operational Performance

However, applying these benefits to Thailand's food supply chains encounters unique challenges. When viewed through the TOE framework presented in Table 4, the most critical factors for the Thai context encompass three dimensions: 1) Technology complexity and high investment costs pose significant barriers, as inadequate infrastructure in remote areas can lead to food loss and impede traceability efficiency, while with appropriate support, these technologies enable real-time tracking and can substantially reduce waste (Surasak et al., 2019). 2) Organizational constraints, particularly among SMEs, arise from a shortage of skilled personnel and limited readiness to adopt new systems, while targeted training initiatives and cross-sector collaboration have the potential to enhance productivity and drive sustainable innovation (Kittipanya-ngam & Tan, 2020). And 3) Environmental pressures from stringent regulations and global market demands compel stakeholders to enhance transparency and adopt advanced traceability systems to ensure safety and maintain market access (Hassoun et al., 2023).

5. Conclusion and Recommendations

5.1 Conclusion

First, by integrating IoT, Blockchain, and AI, companies gain real-time visibility into every step of the supply chain, maintain tamper-proof records, and verify product origins instantly. These capabilities speed up decision-making and product recalls, improve quality control, and reduce costs through automation and better risk management. Finally, while Thailand's supportive policies, industry standards, and collaboration networks help drive adoption, high upfront investment costs, patchy digital infrastructure in rural areas, and a shortage of skilled staff still pose serious obstacles.

To overcome these challenges, entrepreneurs can kick off small-scale IoT pilots at critical sites, partner with experienced Blockchain vendors, and use open-source AI tools for focused analytics (Rui & Sundram, 2024). Government bodies should subsidize initial technology investments, fund digital skills training for SMEs, and standardize data formats across the food supply chain. Coordinated action between the public and private sectors will be key to rolling out transparent, traceable solutions that benefit all stakeholders in Thailand's food industry (Yooyativong & Kamyod, 2023).

5.2 Limitations and Future Research

This study has several limitations that suggest directions for future research: 1) Methodologically, the systematic literature review was confined to the Scopus database. Although Scopus is large, reputable, and comprehensive, this restriction may have excluded relevant studies published in other databases such as Google Scholar, Web of Science, or ScienceDirect. 2) In terms of dependent variables, the study focused on operational performance dimensions of speed, quality, and cost reduction, which may not fully capture impacts in other performance dimensions. 3) Regarding generalizability, the scope was limited to the food industry, so the findings may not be directly applicable to other industries with different contextual factors. Future research should conduct quantitative or qualitative empirical investigations by collecting primary data from food industry practitioners in Thailand to test the proposed framework and gain deeper insights into contextual barriers.

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