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A Blockchain-Based Framework for Secure and Transparent Food Supply Chain Traceability

Zahra Mobini[1,*], Nasim Nahavandi[1], Motahareh Deghan[1]

1Department of Industrial and Systems Engineering, Tarbiat Modares University; Zahra_mobini@modares.ac.ir, N_nahavandi@modares.ac.ir, M_dehghan@modares.ac.ir.

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Abstract

Persistent concerns regarding product counterfeiting and food safety failures necessitate the implementation of sophisticated quality management frameworks capable of ensuring real-time transparency within food distribution networks. This research introduces and validates a blockchain-centric traceability architecture specifically optimized for highly perishable commodities, such as meat products. Our model mitigates systemic deficiencies, notably the delayed detection of hazardous contamination, pervasive information asymmetry, and operational fragmentation among supply chain participants. Adopting a design science research paradigm, the study integrates smart contract technology on a decentralized ledger to facilitate automated, immutable data logging across all supply chain tiers. Through expert-driven evaluation—incorporating metrics such as transparency, system reliability, data fidelity, latency, and cost-efficiency—the research demonstrates that blockchain integration significantly enhances product visibility, fosters stakeholder trust, and optimizes emergency response times during safety incidents. Ultimately, this study provides a scalable, secure, and technologically robust framework, offering a transformative pathway for securing food supply chains and bolstering public health safeguards.

Keywords: Distributed ledger technology, Agri-food supply chain, Traceability system, Intelligent contracts, Supply chain visibility.

1 | Introduction

Ensuring the integrity and safety of food supply networks has become a primary global priority, driven by the escalating demands of a growing population and a rising consumer focus on quality. Nevertheless, contemporary food logistics remain plagued by systemic vulnerabilities, ranging from persistent accountability gaps and frequent safety violations to fragmented communication among network participants. Within the agri-food industry, the importance of end-to-end product visibility cannot be overstated; it remains a fundamental requirement for meeting regulatory mandates, safeguarding public health, and fostering consumer confidence.

Corresponding Author: Zahra_mobini@modares.ac.ir

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Current industry practices typically rely on centralized, siloed database architectures. These traditional frameworks present significant drawbacks: they are inherently susceptible to data tampering, lack real-time synchronization, and suffer from sluggish responses during critical food-borne illness outbreaks. Furthermore, the dependency on archaic methods—such as manual documentation and simple barcoding—alongside a heavy reliance on intermediaries, further erodes data accuracy and operational. As these chains become increasingly globalized and intricate, such operational inefficiencies present escalating risks to both logistical efficacy and public welfare.

Recent research has increasingly identified blockchain as a transformative digital infrastructure for addressing traceability and trust deficiencies in food supply chains. Its decentralized and immutable architecture enables transparent, verifiable, and real-time information exchange among multiple actors while reducing the risk of unauthorized data alteration. In addition, the integration of smart contracts facilitates automated execution of predefined rules and transactions, thereby minimizing human intervention, reducing delays, and improving coordination efficiency (Zineb et al., 2024). Supporting this line of inquiry, Mobini, Nahavandi, and Dehghan (2025) emphasize that blockchain-powered traceability systems can significantly improve trust, transparency, and real-time monitoring in food supply chains, highlighting their potential to strengthen information reliability and support more responsive decision-making across interconnected supply chain stages.

Despite these advantages, existing literature often overlooks the specific constraints of highly perishable goods, such as meat products, where rapid contamination detection is a matter of immediate safety. Many studies discuss blockchain-enabled traceability at a general level, yet fewer offer tailored frameworks that address the operational sensitivity of meat supply chains, where spoilage, contamination risk, and timing are especially critical.

This study bridges this critical research gap by introducing a custom-designed, blockchain-based traceability system optimized for meat supply chains. The proposed framework facilitates a secure and near real-time mechanism for tracking product journeys, thereby curbing fraudulent activities, bolstering safety standards, and strengthening multi-stakeholder trust. Additionally, this research demonstrates how smart contract deployment can standardize, automate, and streamline traceability workflows in a sector where accuracy and response speed are essential.

2. Literature Review

Food traceability has become a critical requirement for ensuring food safety, quality assurance, and regulatory compliance across modern supply chains. Traditional traceability systems often rely on centralized databases, which may suffer from data fragmentation, limited transparency, and vulnerability to unauthorized modifications. These limitations can hinder the rapid identification of contamination sources and reduce stakeholder trust throughout the supply chain.

Blockchain technology has emerged as a promising solution for addressing these challenges by providing decentralized, transparent, and tamper-resistant data management mechanisms. Several studies have explored the application of blockchain technology in food supply chains. For example, Salah et al. (2019) proposed a blockchain-based soybean traceability framework, while Jaya et al. (2021) developed a blockchain-enabled traceability system for fishery products. Similarly, Marchese and Tomarchio (2022) introduced a blockchain-based approach for agri-food supply chain management, and Kechagias et al. (2023) developed an Ethereum-based distributed application to enhance food traceability.

Recent studies have further expanded blockchain applications through the integration of complementary technologies such as IoT, artificial intelligence, and advanced governance mechanisms. Cao et al. (2022) investigated blockchain-based governance solutions for the beef industry, while Zineb et al. (2024) proposed a blockchain-enabled logistics traceability framework. Furthermore, Saidu et al. (2025) highlighted the growing convergence of blockchain, IoT, and AI technologies for next-generation traceability systems.

Despite these advancements, several research gaps remain. First, many studies focus on conceptual frameworks or pilot implementations without comprehensive evaluation of deployment feasibility. Second,

only a limited number of studies specifically address meat supply chains, where product perishability and food safety concerns require highly reliable traceability mechanisms. Third, deployment cost assessment and expert-based validation are often overlooked in existing blockchain traceability research.

To address these gaps, this study proposes and implements a blockchain-based meat traceability system utilizing Ethereum smart contracts and IPFS decentralized storage. In addition to practical system implementation, the proposed framework incorporates deployment cost analysis and expert-based evaluation to assess its operational feasibility and effectiveness. Table 1 summarizes the main characteristics of representative studies, while Table 2 presents the identified research gaps addressed by the proposed framework.

Table 1. A brief description of previous research.

Author/Year	Research Objective	Application Area	Technology Used	Contribution/Innovation
Malik etal., 2024	Need for traceability in perishable products due to fraud and contamination	General Traceability	N/A	Emphasized the importance in perishable goods
Kshetri, 2018	Cost reduction and efficiency via smart contracts	General SCM	Smart Contracts	Impact on cost and efficiency
Jaya et al., 2021	Improve traceability and reduce fraud in seafood	Seafood	Hyperledger Fabric	High performance and food safety
Dutta et al., 2020	Enhance efficiency, reduce risks	Agriculture	Public Blockchain	Reduce intermediaries, automation
Yang et al., 2021	Full transparency from production to consumption	Food Chain	Blockchain	Complete view of the supply chain
Chen et al., 2017	Transparency in the food supply chain	Food Supply Chain	Blockchain	Ensure safety and quality
Salah et al., 2019	Soybean traceability via Ethereum	Agriculture	Ethereum	Remove the central authority
Kechagias et al., 2023	Olive oil traceability Dapp	Olive Oil	Ethereum	Compliance with international standards
Ehsan et al., 2022	Decentralized agri supply chain	Agriculture	Blockchain + Smart Contracts	Enhance trust and transparency
Marchese& Tomarchio, 2022	Agri-food traceability model	Agriculture	Hyperledger Fabric	Scalability, automation
Zineb et al., 2024	Real-time product monitoring (BlockSup)	General SCM	Private Blockchain + IoT	Real-time alerts and secure storage
Cao et al., 2022	Governance in the beef supply chain	Meat Industry	Multisignature + Blockchain	End-to-end transparency
Saidu et al., 2025	Tech trends in traceability	General	Ethereum, Hyperledger	AI/IoT integration, challenges in standardization
Chen et al., 2025	Dual-chain safe food traceability system	Food Production & Distribution	Ethereum, RAFT, PBFT	Reliability and performance improvements

Table 2. Research gap analysis of blockchain-based traceability systems in food supply chains.

Study	Blockchain Platform	Real-World Implementation	Smart Contract Integration	Focus on Meat Supply Chain	Cost Evaluation	Expert-Based Validation	Main Limitation
Salah et al. (2019)	Ethereum	✓	✓	✗	✗	✗	Focused on soybean traceability without industry-specific validation
Jaya et al. (2021)	Hyperledger Fabric	✓	Limited	✗	✗	✗	Restricted to seafood supply chains
Ehsan et al. (2022)	Blockchain-Based Framework	✗	✓	✗	✗	✗	Conceptual model without implementation
Marchese & Tomarchio (2022)	Hyperledger Fabric	✓	✓	✗	✗	✗	Limited evaluation of practical deployment costs

Kechagias et al. (2023)	Ethereum	✓	✓	✗	✗	✗	Focused on olive oil traceability only
Zineb et al. (2024)	Private Blockchain + IoT	✓	Limited	✗	✗	✗	Emphasis on logistics monitoring rather than full traceability
Cao et al. (2022)	Multisignature Blockchain	✓	✓	✓	✗	✗	Focused on governance mechanisms rather than complete traceability architecture
Chen et al. (2025)	Ethereum + RAFT/PBFT	✓	✓	✗	Limited	✗	Focused primarily on system performance and reliability
Saidu et al. (2025)	Review Study	✗	✗	Partial	✗	✗	Review-based study without practical implementation
This Study	Ethereum + IPFS	✓	✓	✓	✓	✓	Provides an implemented blockchain-based traceability system for meat products with smart contract automation, deployment cost analysis, and expert-based evaluation

Fig. 1. demonstrates the positioning of the proposed study within the blockchain-enabled food traceability literature. The framework summarizes major research themes, compares existing studies across critical implementation dimensions, identifies unresolved research gaps, and demonstrates how the proposed blockchain-based system addresses these gaps through a practical implementation, smart contract automation, decentralized storage, and comprehensive evaluation.

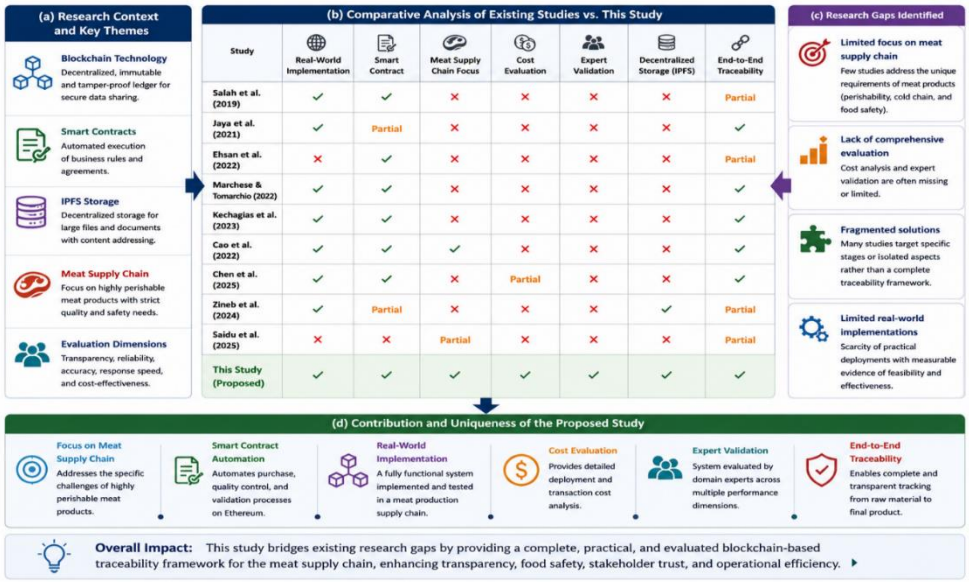


Fig. 1. Research Positioning Framework of the Proposed Blockchain-Based Meat Traceability System.

3 | Proposed System

The proposed system aims to improve transparency, traceability, and trust in the meat supply chain through the integration of blockchain technology, smart contracts, and decentralized storage. The framework was developed on the Ethereum blockchain platform and utilizes the InterPlanetary File System (IPFS) to securely store and manage product-related information.

The system supports the main stakeholders involved in the meat supply chain, including suppliers, purchasing managers, warehouse personnel, quality control officers, and testing experts. Smart contracts automate key

business processes such as raw material procurement, product registration, quality inspection, and transaction validation. This automation reduces manual intervention, improves process consistency, and enhances data reliability.

Fig. 2 illustrates the overall architecture of the proposed system. Product information and transaction records are securely registered on the blockchain, while supporting documents are stored in IPFS and linked through cryptographic hashes. This combination ensures data integrity, transparency, and secure access to traceability information throughout the supply chain lifecycle.

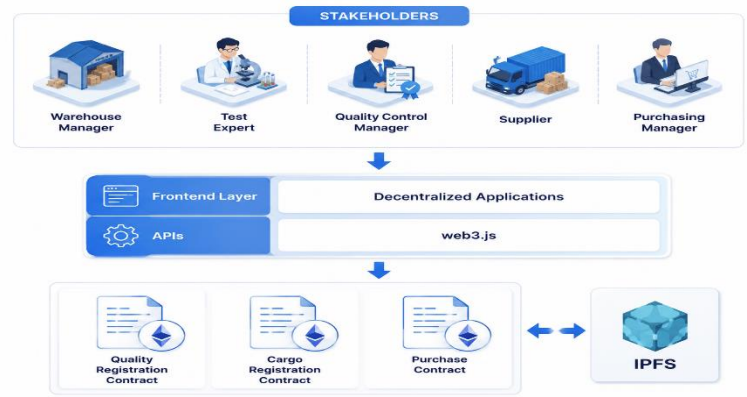


Fig. 2. **Proposed multi-layered blockchain architecture for meat supply chain traceability**.

The architecture consists of three main layers: stakeholders, decentralized storage, and blockchain services. Stakeholders interact with the system through a decentralized application (DApp), while product-related documents are stored in IPFS. Ethereum smart contracts manage transaction execution, data validation, and traceability operations. The integration of these components provides a secure and transparent environment for tracking products across different stages of the meat supply chain. *Fig. 3*. shows the interaction between different parts of the supply chain in the proposed system, which is explained below.

Purchase of raw materials: In this scenario, the process of purchasing raw materials is completely managed through the system. First, the purchasing expert registers the purchase request in the system. The supplier then reviews the request and after approval, sends the raw materials to the company's warehouse. After receiving the material, the consignee records the receipt information and the first quality control officer confirms the initial quality of the material.

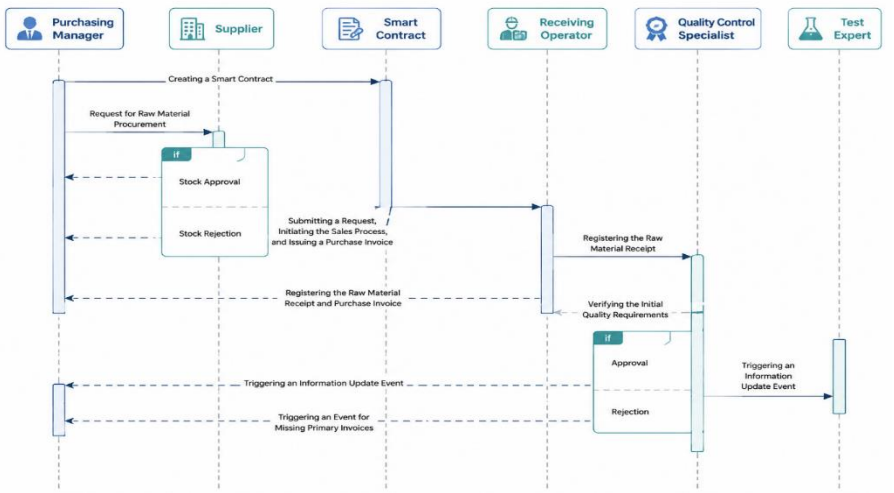


Fig. 3. Interaction sequence diagram between meat supplier company, buyer, smart contract, warehouse, quality control officer and test expert.

4 | Design Science Research Implementation

This study follows the Design Science Research (DSR) methodology to develop and evaluate a blockchain-based traceability system for the meat supply chain. DSR provides a structured approach for designing technological artifacts that address practical organizational problems while contributing to academic knowledge.

Following the DSR process proposed by Hevner et al., the research began with problem identification, focusing on the challenges of transparency, traceability, and trust in meat supply chains. Subsequently, system requirements were defined, and a blockchain-based solution was designed using Ethereum smart contracts and IPFS decentralized storage. The developed artifact was then implemented and evaluated through deployment cost analysis and expert-based assessment to examine its feasibility and effectiveness in supporting secure product traceability.

4.1 | User Interface Design

The user interface design constitutes a critical component enabling stakeholder interaction with the system. We utilized HTML and JavaScript to develop an intuitive and responsive interface that facilitates the recording of purchase requests and product information. The interface design prioritizes usability while maintaining the necessary security protocols for blockchain interaction, allowing stakeholders to efficiently manage and track products throughout the supply chain.

4.2 | Development and Implementation

In line with the DSR methodology's design and development phase, we created the technological artifact through iterative development cycles. Each iteration incorporated feedback from stakeholders and addressed emerging design challenges.

System development and implementation were conducted in the Remix integrated development environment, which offers comprehensive tools for Ethereum smart contract development and testing. The final system consists of an integrated blockchain with five interconnected smart contracts: three raw material purchase contracts, one cargo registration contract, and one quality registration contract. These contracts interact both directly and indirectly to execute processes and enable comprehensive product tracking throughout the supply chain.

The raw material purchase contract specifically manages the procurement of meat ingredients. Various stakeholders interface with this contract according to their designated roles in the system, accessing critical information such as meat type, quantity, date, price, and relevant stakeholder addresses (purchasing manager, supplier, and warehouse manager).

5 | Testing And Evaluation

This section presents the evaluation of the proposed tracking system, focusing on two key aspects: cost analysis and expert-based assessment.

5.1 | Cost Evaluation

The cost evaluation was conducted using the EtraScan environment, where various smart contracts related to purchase agreements, cargo registration, and quality assessment were deployed. The transaction fees associated with both the creation and execution of these contracts were calculated. Table 3 summarizes the costs in terms of both Ether (ETH) and US Dollars (USD).

Table 3. Cost breakdown for smart contract deployment and execution.

Method	TxnFee (ETH)	TxnFee (USD)
Create BuyingMeat Contract	0.008527749	22.20
Send BuyingMeat Request	0.000296033	0.77
Accept BuyingMeat Request	0.00119101	3.11
Create CargoRegistration Contract	0.027204737	71.00
Accept Meat Receipt	0.003121492	8.10
Perform Quality Check	0.003190302	8.30
Create QualityRegister Contract	0.053480552	140.00
Quality Test	0.004831729	12.60
Validate Stage 1	0.001864461	4.80

5.2 | Expert-Based Evaluation

To assess the system from a qualitative perspective, feedback was gathered from domain experts. A set of structured questions was designed to evaluate aspects such as usability, accessibility, perceived impact on product quality, and user satisfaction. Based on expert feedback, the integration of blockchain significantly enhances stakeholder trust by ensuring secure and transparent data management. Despite the promising outcomes of the blockchain-based tracking system, several challenges emerged during its development and evaluation. One of the primary obstacles was the complexity of blockchain technology, which posed a barrier for many stakeholders unfamiliar with its technical intricacies. To overcome this, the project incorporated targeted educational initiatives, including simplified training resources and awareness sessions, aimed at improving users' understanding and acceptance of the system. Finally, skepticism among supply chain partners posed a challenge to widespread adoption. Building trust and ensuring stakeholder buy-in required proactive engagement.

5.3 | Comparative Performance Analysis

To further assess the practical value of the proposed blockchain-based traceability system, a comparative analysis was conducted between the conventional centralized traceability approach commonly used in food supply chains and the proposed blockchain-enabled framework. The comparison focuses on key operational and managerial dimensions that directly influence food safety, transparency, and supply chain efficiency. The evaluation criteria were selected based on prior studies that identified transparency, immutability, auditability, stakeholder trust, and operational efficiency as critical performance dimensions in blockchain-enabled supply chains (Kshetri, 2018; Saberi et al., 2019; Casino et al., 2019). Table 4 presents the comparative evaluation results.

Table 4. Comparison of traditional and blockchain-based traceability systems.

Performance Criterion	Traditional Traceability System	Proposed Blockchain-Based System
Data Transparency	Limited visibility across stakeholders	Real-time shared visibility among authorized participants
Data Integrity	Vulnerable to modification and manipulation	Immutable and tamper-resistant records
Traceability Speed	Time-consuming manual investigation	Instant access to product history and transactions
Stakeholder Trust	Dependent on intermediaries and centralized authorities	Enhanced through decentralized verification
Fraud Prevention	Limited capability to detect data manipulation	Strong protection through cryptographic validation
Auditability	Requires extensive document verification	Automated and transparent audit trail
Information Availability	Fragmented across multiple databases	Unified and synchronized distributed ledger
Response to Contamination Events	Delayed identification and recall process	Rapid source identification and targeted recalls
System Security	Vulnerable to single points of failure	Distributed architecture improves resilience
Operational Efficiency	High administrative effort	Automated processes through smart contracts

The results demonstrate that the proposed blockchain-based framework provides significant advantages over traditional traceability systems. One of the most important improvements is the enhancement of transparency throughout the supply chain. Since all authorized stakeholders have access to a shared and synchronized ledger, information asymmetry is substantially reduced. Furthermore, blockchain's immutable structure prevents unauthorized modification of records, thereby improving data integrity and reliability, which is consistent with the findings reported by Kshetri (2018) and Saberi et al. (2019).

Another notable advantage is the acceleration of traceability processes. In conventional systems, identifying the source of contamination often requires extensive manual investigation across multiple databases and organizational boundaries. In contrast, the proposed system enables real-time access to historical transaction data, allowing rapid identification of affected batches and reducing response times during food safety incidents. This capability is particularly important in perishable food supply chains, where delays can lead to significant quality losses and public health risks.

The implementation of smart contracts further contributes to operational efficiency by automating validation procedures and business rules. This reduces administrative workload, minimizes human errors, and increases consistency across supply chain operations. Moreover, the decentralized architecture eliminates reliance on a single controlling entity, thereby improving system resilience and strengthening stakeholder trust. These advantages are aligned with the broader blockchain supply chain literature, which emphasizes the role of distributed ledgers in improving coordination, traceability, and governance (Casino et al., 2019; Saberi et al., 2019).

Overall, the comparative analysis confirms that the proposed blockchain-based traceability system offers substantial improvements in transparency, security, traceability, and operational performance. These findings support the feasibility of adopting blockchain technology as a strategic solution for enhancing food supply chain management, particularly in highly perishable industries such as meat production.

5.4 | Discussion and Managerial Implications

The results of this study demonstrate that blockchain technology can effectively improve transparency, traceability, and trust within meat supply chains. By integrating Ethereum smart contracts with IPFS storage, the proposed framework provides a secure and immutable environment for recording and verifying supply chain transactions. The comparative analysis indicates that the proposed system outperforms conventional traceability approaches in terms of data integrity, information availability, auditability, and response speed during food safety incidents.

These findings are consistent with previous studies that highlight the potential of blockchain technology to enhance visibility and reduce information asymmetry across supply chain networks (Kshetri, 2018; Saberi et al., 2019). However, unlike many existing studies that primarily present conceptual frameworks, the proposed research demonstrates a practical implementation tailored to the meat supply chain, supported by deployment cost evaluation and expert assessment.

From a managerial perspective, the system enables stakeholders to access reliable real-time information, facilitating faster decision-making and more effective responses to quality and contamination issues. The use of smart contracts also reduces administrative effort by automating business processes and minimizing human errors. Furthermore, improved traceability can support targeted product recalls, reducing unnecessary waste and associated financial losses. Enhanced transparency additionally strengthens consumer trust and facilitates compliance with food safety regulations.

Overall, the findings suggest that blockchain technology can serve as an effective digital transformation tool for food supply chains by improving operational efficiency, product traceability, stakeholder trust, and supply chain resilience.

5.5|Limitations and Future Research

Despite the promising results obtained from the proposed blockchain-based traceability system, several limitations should be acknowledged. First, the current implementation was developed and evaluated within the context of a specific meat production supply chain. Consequently, the findings may not be directly generalizable to other food industries with different operational structures, regulatory requirements, and stakeholder interactions. Future studies should validate the proposed framework across various food supply chains, including dairy, seafood, and fresh agricultural products.

Second, the system was implemented using the Ethereum blockchain platform, which may face scalability challenges when processing a large volume of transactions. As the number of stakeholders and recorded events increases, transaction throughput and network congestion may affect system performance. Additionally, transaction fees (gas costs) associated with blockchain operations may become significant in large-scale deployments. Future research may investigate alternative blockchain architectures, such as consortium or permissioned blockchains, to improve scalability and cost efficiency.

Third, although the proposed framework incorporates decentralized data storage through IPFS and secure transaction management through smart contracts, the evaluation was primarily based on deployment cost analysis and expert assessment. More comprehensive empirical evaluations involving real-world operational data, quantitative performance measurements, and longitudinal case studies would provide stronger evidence regarding the effectiveness of blockchain-enabled traceability systems.

Another limitation relates to data acquisition and monitoring. The current system relies on manual data entry by supply chain participants. While blockchain ensures the integrity of recorded information, it cannot guarantee the accuracy of data at the point of entry. Future studies could integrate Internet of Things (IoT) devices and sensor technologies to automate data collection related to product location, temperature, humidity, and storage conditions, thereby reducing human intervention and improving data reliability.

Furthermore, recent advancements in artificial intelligence (AI) and machine learning present valuable opportunities for enhancing food supply chain management. Future research could investigate the integration of blockchain with AI-based predictive analytics to identify potential contamination risks, forecast product quality deterioration, and support proactive decision-making throughout the supply chain.

Finally, future studies may explore the development of digital twin-based supply chain models that combine blockchain, IoT, and advanced analytics to create intelligent and adaptive traceability ecosystems. Such integrated approaches have the potential to further improve transparency, resilience, sustainability, and operational performance in modern food supply chains.

Overall, while the proposed framework demonstrates the practical feasibility of blockchain-enabled traceability in the meat industry, additional research is required to address scalability, automation, interoperability, and intelligent decision-support capabilities in broader industrial contexts.

6|Conclusion

The present study investigated the role of blockchain technology in strengthening transparency, efficiency, and stakeholder trust within the meat supply chain. By mapping real-world operational processes and developing a blockchain-based architectural model, the research proposed a smart traceability mechanism capable of securely overseeing raw material sourcing, quality inspection, and storage functions through Ethereum smart contracts. The findings reveal that the proposed framework markedly enhances traceability performance by ensuring end-to-end visibility across all critical stages, from raw material origin to final processing. Furthermore, the provision of immutable, real-time data contributes to greater trust among supply chain actors—including producers, suppliers, distributors, and consumers—by facilitating more informed decision-making and

improving risk management capabilities. Overall, the study confirms the considerable promise of blockchain as a transformative technology for addressing fundamental food supply chain challenges and supporting the transition toward a more secure, intelligent, and sustainable logistics ecosystem.

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