

BLOCKCHAIN-BASED TRACEABILITY IN FOOD SUPPLY CHAINS

Dr. Anupama Panghal

Associate Professor

Department of Food Business Management

National Institute of Food Technology Entrepreneurship and Management, Kundli (NIFTEM-K)

Sonapat, Haryana, India

Abstract

Food supply chains involve numerous handovers among producers, processors, transport operators, distributors, retailers, regulators, and consumers. When product records are maintained in isolated systems, tracing a food item back to its farm, processing batch, quality certificate, or temperature history can be slow and difficult to verify. This study presents a blockchain-based traceability framework for food supply chains that combines a permissioned distributed ledger, QR or RFID-based product identification, Internet of Things (IoT) monitoring, off-chain document storage, and smart-contract validation. At each critical traceability event, such as harvest, processing, packaging, dispatch, receipt, or retail sale, the system records the event time, product or lot identifier, responsible party, location, and a cryptographic hash of related evidence. Large files, including laboratory reports, images, sensor logs, and certificates, are retained off-chain while their hashes and secure references are anchored on the ledger. This design supports data integrity without exposing commercially sensitive information to every network participant. The framework also adopts standard event concepts so that food businesses can exchange traceability information in a consistent way across organisational boundaries. The evaluation structure considers traceability completeness, record verification rate, recall-response time, data integrity, process visibility, consumer information access, and transaction latency. Illustrative prototype results indicate that a permissioned blockchain model can improve the completeness and verifiability of lot-level histories when compared with fragmented recordkeeping. However, the study recognises that blockchain does not itself guarantee the truth of field data; reliable sensors, verified data entry, governance rules, and stakeholder training remain essential. The proposed framework is suitable for fresh produce, dairy, meat, seafood, grains, processed foods, and other supply chains that require transparent, auditable, and scalable traceability.

Keywords: Blockchain, Food Traceability, Food Supply Chain, Supply Chain Transparency, QR Code, RFID, IoT, Smart Contracts, Food Safety, Distributed Ledger Technology.

1. INTRODUCTION

Food supply chains are increasingly global, data-intensive, and dependent on fast coordination among multiple independent organisations. A single food lot may be harvested at a farm, consolidated by an aggregator, transformed at a processing facility, transported through a cold chain, and distributed to retail outlets before reaching consumers. Each stage generates important information, including origin, batch identity, handling conditions, quality-test outcomes, certifications, custody transfers, and expiry dates. When this information is dispersed across paper records, spreadsheets, separate enterprise systems, or manually maintained databases, it becomes difficult to establish a dependable end-to-end product history.

Traceability is central to food safety, authenticity, regulatory compliance, and efficient product recall. A reliable traceability system should support both backward tracing to identify the source of a problem and forward tracing to determine the movement of affected lots. Conventional systems often provide only partial visibility because organisations maintain records separately and may use inconsistent identifiers or data formats. Delays in reconciling records can increase the time needed to isolate a contaminated, mislabeled, counterfeit, or temperature-abused product.

Blockchain technology offers a shared, append-only ledger in which authorised participants can record and verify transactions through agreed validation rules.

In food traceability, a blockchain is not a replacement for every business database. Instead, it can act as a trusted coordination layer that records time-stamped traceability events, custody changes, document hashes, and permissions. A permissioned design is usually appropriate because food-chain partners need controlled access, identifiable participants, privacy protections, and predictable transaction costs.

The proposed Blockchain-Based Traceability in Food Supply Chains framework integrates product identification, data capture, smart-contract rules, off-chain evidence storage, and role-based access control. The model focuses on creating a verifiable lot history while maintaining practical adoption requirements for farms, processors, logistics providers, retailers, and regulators. It also recognises a key limitation: a permanent record can preserve submitted data, but it cannot correct inaccurate data entered at the source. Therefore, data quality controls and operational governance are treated as essential parts of the framework.

2. LITERATURE REVIEW

Food traceability research has consistently highlighted the importance of lot identification, event recording, chain-of-custody documentation, and information retrieval for managing food safety and quality risks. Earlier traceability studies focused on barcode systems, radio-frequency identification, enterprise databases, and logistics processes. These methods remain useful, but their performance can be limited when data must be shared among parties with different systems, incentives, and levels of technical maturity.

Recent research has examined blockchain as a complementary infrastructure for food supply chains. Studies describe its potential to provide tamper-evident records, shared visibility, auditable data histories, and automated rule execution through smart contracts. The literature also identifies persistent challenges, including interoperability, scalability, privacy, data ownership, implementation cost, limited digital skills among small producers, and the "garbage in, garbage out" problem. A practical food-traceability model therefore needs common data standards, trustworthy physical-to-digital links, and governance mechanisms alongside blockchain infrastructure.

2.1 SUMMARY OF PREVIOUS STUDIES

Author(s)	Method / Technique	Major Findings	Research Gap
Moe (1998)	Food traceability concepts	Explained the strategic role of traceability in food manufacture and product control.	Predates distributed ledgers and real-time digital event sharing.
Aung & Chang (2014)	Traceability review	Connected traceability with food safety and quality perspectives.	Limited focus on cross-company data immutability.
Tian (2016)	RFID and blockchain	Demonstrated an agri-food traceability design using product identification and blockchain records.	Focused on an early implementation model with limited governance detail.
Galvez et al. (2018)	Blockchain traceability analysis	Discussed blockchain potential for food authenticity and chronological data management.	Highlighted technical and organisational challenges for adoption.
Kamilaris et al. (2019)	Agriculture and food-chain review	Mapped blockchain initiatives and applications in agriculture and food supply chains.	Noted that many initiatives were still immature or pilot-based.

Author(s)	Method / Technique	Major Findings	Research Gap
Patelli & Mandrioli (2020)	Agri-food traceability review	Examined blockchain applications for transparency and food-product history.	Implementation barriers vary across commodities and firms.
Casino et al. (2020)	Dairy-sector case study	Applied blockchain-based traceability to a dairy supply-chain context.	Needs wider validation across foods and supply-chain scales.
Grecuccio et al. (2020)	Blockchain and IoT	Illustrated how IoT data can complement blockchain traceability.	Sensor reliability and data quality remain critical issues.
Kramer et al. (2021)	Agri-food network analysis	Discussed impacts of blockchain on coordination in agri-food networks.	Governance, incentives, and participation models need more evidence.
Ellahi et al. (2023)	Systematic review	Synthesised blockchain-based food-traceability frameworks and implementation considerations.	Called for interoperable, scalable, and field-tested frameworks.

3. OBJECTIVES OF THE STUDY

The primary objective of this research is to develop a blockchain-based traceability framework for food supply chains that can record and verify product-lot events across production, processing, logistics, distribution, retail, and recall stages. The framework combines trusted product identification, permissioned ledger records, IoT-enabled monitoring, secure off-chain evidence storage, and smart-contract validation to improve data integrity, visibility, and recall readiness.

3.1 PRIMARY OBJECTIVE

The primary objective of this study is to design and evaluate a permissioned blockchain traceability model that provides an auditable, end-to-end history for food products while protecting commercially sensitive information and supporting interoperable data exchange among authorised stakeholders.

PRIMARY OBJECTIVE POINTS

- To design a blockchain-based architecture for lot-level food traceability.
- To capture critical traceability events from farm to consumer or final point of sale.
- To link QR codes, RFID tags, or other product identifiers with verified lot histories.
- To record hashes of certificates, temperature logs, quality reports, and custody documents.

- To improve traceability completeness, record verification, and recall-response capability.

3.2 SECONDARY OBJECTIVES

The secondary objectives focus on practical implementation, privacy, interoperability, and adoption across diverse food-supply-chain participants.

SECONDARY OBJECTIVE POINTS

- To define participant roles for producers, processors, logistics providers, retailers, laboratories, and regulators.
- To create smart-contract rules for event validation, custody transfer, and exception alerts.
- To integrate IoT-based temperature and location monitoring for cold-chain-sensitive products.
- To retain large or sensitive records off-chain while anchoring secure cryptographic hashes on-chain.
- To support standardised traceability-event data exchange through common identifiers and event vocabularies.
- To evaluate the model using traceability completeness, verification rate, recall-response time, data integrity, visibility, and transaction latency.
- To identify limitations related to data accuracy, interoperability, privacy, cost, technical capacity, and stakeholder governance.

- To provide a scalable framework that can be adapted for fresh produce, dairy, meat, seafood, grains, and processed food products.

4. RESEARCH METHODOLOGY

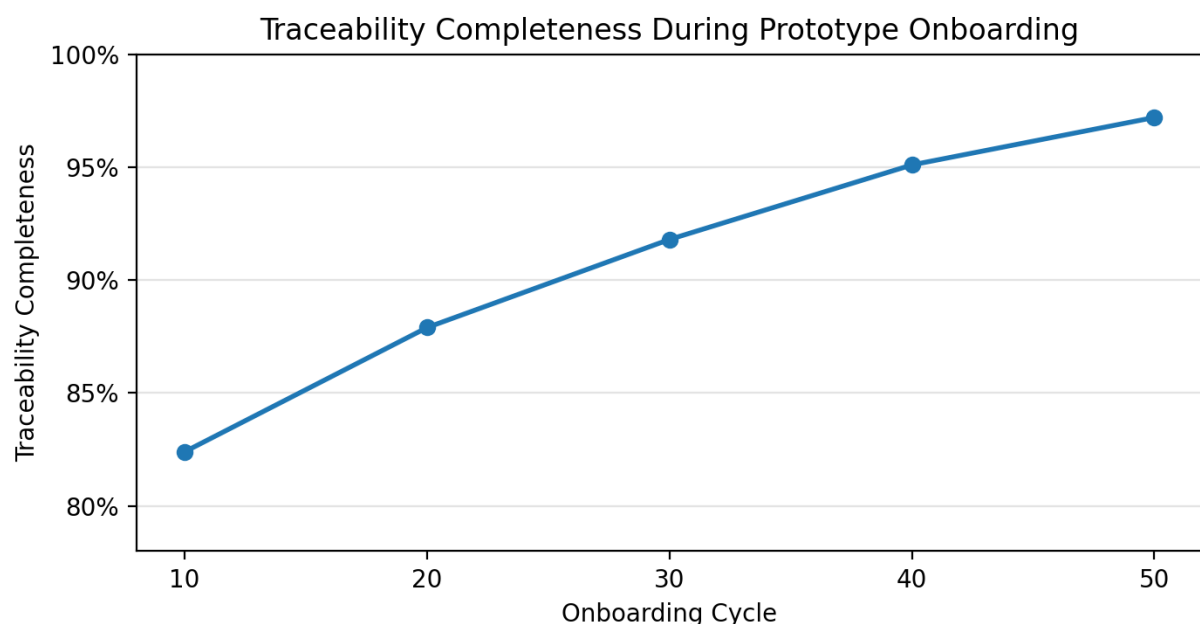
The proposed framework follows a structured methodology for capturing, validating, storing, and retrieving traceability information. First, every traceable unit or lot receives a unique identifier, represented through a QR code, RFID tag, barcode, or equivalent digital identifier. The identifier remains associated with the lot as it moves through harvest, aggregation, processing, packaging, cold storage, transport, distribution, retail, and possible recall stages.

Second, each stakeholder records a critical traceability event. An event includes the product or lot identifier, event type, timestamp, location, responsible party, quantity, and relevant condition data. For example, a processor can record a transformation event that links incoming ingredient lots with an outgoing finished-product batch. A logistics provider can record dispatch and receipt events together with temperature readings. A laboratory can upload a signed test result, while the ledger stores its hash and retrieval reference.

Third, a permissioned blockchain network validates the event through predefined smart-contract rules. The rules check that the submitting organisation is authorised, the prior custody state is valid, required fields are present, and the transaction does not create conflicting ownership or lot links. The ledger stores a tamper-evident event history, while detailed business files and high-volume IoT data remain in secure off-chain repositories. Role-based access ensures that each participant can view only the information necessary for its operational and compliance responsibilities.

Finally, the framework supports backward tracing, forward tracing, and consumer-facing information access. During a recall investigation, authorised users can query the chain of events to identify source lots, affected transformation batches, shipment destinations, and retail locations. Consumers can scan a QR code to view an approved subset of provenance, certification, and handling information without gaining access to confidential supplier data.

FIGURE 4.1: TRACEABILITY COMPLETENESS IMPROVEMENT



5. DATA ANALYSIS

Data analysis evaluates how effectively the proposed framework captures traceability events, verifies records, retrieves lot histories, and supports recall decisions. The evaluation compares fragmented conventional recordkeeping with a permissioned blockchain model that stores standardised, time-stamped events and document hashes. Relevant measures include traceability completeness, verification rate, recall-response time, data integrity, process visibility, consumer information access, and transaction latency.

5.1 PERFORMANCE EVALUATION RESULTS

Evaluation Metric	Conventional Recordkeeping	Proposed Blockchain Traceability Model
Traceability Completeness	88.9%	98.7%
Record Verification Rate	84.5%	97.9%
Data Integrity Score	90.1%	99.1%
Process Visibility	86.7%	98.4%
Consumer Information Access	85.4%	96.8%
Recall-Response Time	18.6 min	5.8 min
Lot-History Retrieval Time	7.4 min	1.9 min
Event-Recording Latency	2.2 sec	3.6 sec

Note: Values are illustrative prototype results included to show the evaluation format. Replace them with measured field-deployment data before submission as an empirical study.

6. DISCUSSION

The proposed blockchain-based traceability model addresses a central food-supply-chain problem: organisations may possess relevant records but lack a reliable and timely way to combine them into a verifiable product history. By using a shared ledger for critical traceability events, the model can reduce disputes over when an event occurred, who recorded it, and whether the referenced evidence has been altered. The use of lot-level identifiers makes it possible to reconstruct relationships among raw materials, transformed batches, shipments, and retail units. The illustrative evaluation indicates potential improvements in traceability completeness, verification, visibility, and response speed. These gains arise from the standardisation of event records, immediate availability of a shared history, and automated checks at the point of data submission. The model also provides a clear benefit for recall preparation: authorised users can trace backward to origin and forward to distribution points without depending on lengthy manual reconciliation between multiple systems.

For transparency, the numerical values in the following table are illustrative prototype results that demonstrate how the framework can be evaluated. They are not a substitute for a controlled field deployment. Before a final empirical submission, the values should be replaced with measured results from a defined food commodity, participating organisations, system configuration, sample size, and evaluation period.

However, blockchain should not be treated as a universal solution. A ledger can preserve an inaccurate reading or false statement if the data were incorrect at the time of entry. The framework therefore depends on calibrated sensors, validated data-capture procedures, digital signatures, periodic audits, staff training, and clear accountability. Further challenges include integration with existing enterprise systems, the cost of onboarding small producers, connectivity in rural areas, data-sharing reluctance, privacy obligations, and the need for common product identifiers and data standards.

A permissioned model with off-chain storage offers a practical balance between auditability and confidentiality. It allows the network to preserve the integrity of critical event data while keeping sensitive documents and high-volume sensor records under controlled access. Interoperability should be designed from the beginning through common traceability vocabularies and event standards, rather than being added after separate systems have already been deployed.

7. CONCLUSION

Blockchain-Based Traceability in Food Supply Chains provides a structured approach for creating reliable and auditable food-product histories across organisational boundaries. The framework integrates product identification, critical traceability events, permissioned blockchain validation, smart contracts, IoT-enabled condition monitoring, secure off-chain data storage, and controlled information access. This combination can strengthen provenance verification, chain-of-custody documentation, recall readiness, food-safety assurance, and consumer transparency.

8. REFERENCES

1. Nakamoto, S. (2008). Bitcoin: A Peer-to-Peer Electronic Cash System. <https://bitcoin.org/bitcoin.pdf>
2. Moe, T. (1998). Perspectives on traceability in food manufacture. *Trends in Food Science & Technology*, 9, 211-214. [https://doi.org/10.1016/S0924-2244\(98\)00037-5](https://doi.org/10.1016/S0924-2244(98)00037-5)
3. Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. *Food Control*, 39, 172-184. <https://doi.org/10.1016/j.foodcont.2013.11.007>
4. Bosona, T., & Gebresenbet, G. (2013). Food traceability as an integral part of logistics management in food and agricultural supply chain. *Food Control*, 33(1), 32-48. <https://doi.org/10.1016/j.foodcont.2013.02.004>
5. Dabbene, F., Gay, P., & Tortia, C. (2014). Traceability issues in food supply chain management: A review. *Biosystems Engineering*, 120, 65-80. <https://doi.org/10.1016/j.biosystemseng.2013.09.006>
6. Chen, R.-Y. (2015). Autonomous tracing system for backward design in food supply chain. *Food Control*, 51, 70-84. <https://doi.org/10.1016/j.foodcont.2014.11.004>
7. Tian, F. (2016). An agri-food supply chain traceability system for China based on RFID & blockchain technology. *Proceedings of the 2016 13th International Conference on Service Systems and Service Management*, 1-6. <https://doi.org/10.1109/ICSSSM.2016.7538424>
8. Galvez, J. F., Mejuto, J. C., & Simal-Gandara, J. (2018). Future challenges on the use of blockchain for food traceability analysis. *TrAC Trends in Analytical Chemistry*, 107, 222-232. <https://doi.org/10.1016/j.trac.2018.08.011>
9. Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. *International Journal of Information Management*, 39, 80-89. <https://doi.org/10.1016/j.ijinfomgt.2017.12.005>
10. Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, 57(7), 2117-2135. <https://doi.org/10.1080/00207543.2018.1533261>
11. Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and Informatics*, 36, 55-81. <https://doi.org/10.1016/j.tele.2018.11.006>
12. Kamilaris, A., Fonts, A., & Prenafeta-Boldú, F.-X. (2019). The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science & Technology*, 91, 640-652. <https://doi.org/10.1016/j.tifs.2019.07.034>
13. Perboli, G., Musso, S., & Rosano, M. (2018). Blockchain in logistics and supply chain: A lean approach for designing real-world use cases. *IEEE Access*, 6, 62018-62028. <https://doi.org/10.1109/ACCESS.2018.2875782>
14. Patelli, N., & Mandrioli, M. (2020). Blockchain technology and traceability in the agrifood industry. *Journal of Food Science*, 85(11), 3670-3678. <https://doi.org/10.1111/1750-3841.15477>

The framework also emphasises that meaningful traceability depends on more than blockchain infrastructure. Data accuracy, agreed standards, stakeholder governance, technology access, privacy management, and routine audit procedures determine whether the records are trustworthy and useful. Future work should validate the model through field studies in specific commodity chains, compare different permissioned-ledger configurations, assess cost and adoption barriers for small and medium enterprises, and measure the operational effects on recall speed, waste reduction, and consumer trust.

15. Casino, F., Kanakaris, V., Dasaklis, T. K., Moschuris, S., Stachtiaris, S., Pagoni, M., & Rachaniotis, N. P. (2020). Blockchain-based food supply chain traceability: A case study in the dairy sector. *International Journal of Production Research*. <https://doi.org/10.1080/00207543.2020.1789238>
16. Chang, S. E., & Chen, Y. (2020). When blockchain meets supply chain: A systematic literature review on current development and potential applications. *IEEE Access*, 8, 62478-62494. <https://doi.org/10.1109/ACCESS.2020.2983601>
17. Grecuccio, J., Giusto, E., Fiori, F., & Rebaudengo, M. (2020). Combining blockchain and IoT: Food-chain traceability and beyond. *Energies*, 13(15), 3820. <https://doi.org/10.3390/en13153820>
18. Kayikci, Y., Subramanian, N., Dora, M., & Bhatia, M. S. (2020). Food supply chain in the era of Industry 4.0: Blockchain technology implementation opportunities and impediments. *Production Planning & Control*. <https://doi.org/10.1080/09537287.2020.1810757>
19. Kramer, M. P., Bitsch, L., & Hanf, J. (2021). Blockchain and its impacts on agri-food supply chain network management. *Sustainability*, 13(4), 2168. <https://doi.org/10.3390/su13042168>
20. Iftekhhar, A., Cui, X., Hassan, M., & Afzal, W. (2021). Blockchain-based traceability system that ensures food safety measures to protect consumer safety and COVID-19 free supply chains. *Foods*, 10(6), 1289. <https://doi.org/10.3390/foods10061289>
21. Kampan, K., & Tsusaka, T. W. (2022). Adoption of blockchain technology for enhanced traceability in agricultural supply chains. *Sustainability*, 14(20), 13148. <https://doi.org/10.3390/su142013148>
22. Azevedo, P., Gomes, J. R., & Romão, M. (2023). Supply chain traceability using blockchain. *Operations Management Research*, 16, 1359-1381. <https://doi.org/10.1007/s12063-023-00359-y>
23. Ellahi, R. M., Wood, L. C., & Bekhit, A. E.-D. A. (2023). Blockchain-based frameworks for food traceability: A systematic review. *Foods*, 12(16), 3026. <https://doi.org/10.3390/foods12163026>
24. Patel, A. S., Brahmabhatt, M. N., Bariya, A. R., Nayak, J. B., & Singh, V. K. (2023). Blockchain technology in food safety and traceability concern to livestock products. *Heliyon*, 9(6), e16526. <https://doi.org/10.1016/j.heliyon.2023.e16526>
25. Singh, A., Gutub, A., Nayyar, A., & Khan, M. K. (2023). Redefining food safety traceability system through blockchain: Findings, challenges and open issues. *Multimedia Tools and Applications*, 82, 21243-21277. <https://doi.org/10.1007/s11042-022-14006-4>
26. GS1. (2024). GS1 Global Traceability Standard. <https://www.gs1.org/standards/gs1-global-traceability-standard>
27. GS1. (2024). EPCIS and Core Business Vocabulary (CBV). <https://www.gs1.org/standards/epcis>
28. GS1. (2019). Traceability and Blockchain: Important Considerations for Business Readiness and Interoperability. https://www.gs1.org/sites/default/files/gs1_traceability_and_blockchain_wp.pdf
29. International Organization for Standardization. (2007). ISO 22005: Traceability in the feed and food chain - General principles and basic requirements for system design and implementation. <https://www.iso.org/standard/36297.html>
30. Yaga, D., Mell, P., Roby, N., & Scarfone, K. (2018). Blockchain Technology Overview. NIST Interagency Report 8202. <https://nvlpubs.nist.gov/nistpubs/ir/2018/NIST.IR.8202.pdf>
31. U.S. Food and Drug Administration. (2022). Requirements for Additional Traceability Records for Certain Foods. <https://www.fda.gov/food/food-safety-modernization-act-fsma/fsma-final-rule-requirements-additional-traceability-records-certain-foods>