End-to-End Supply Chain Traceability Using Blockchain

Navang Shah
Dept. of Information Technology
K. J. Somaiya Institute of Technology
Mumbai,India
navang.shah@somaiya.edu

Ojas Narsana
Dept. of Information Technology
K. J. Somaiya Institute of Technology
Mumbai, India
ojas.n@somaiya.edu

Shreya Singh
AI Infrastructure product manager
California
United States of America
shrsing4@cisco.com

Uday Rote
Dept. of Information Technology Cisco
K. J. Somaiya Institute of Technology
Mumbai, India
uday.rote@somaiya.edu

***Abstract*—This work presents an innovative blockchain-based framework designed to enhance end-to-end traceability within modern supply chains, addressing critical challenges such as fragmented visibility, inconsistent data, and a lack of trust between stakeholders. Traditional supply chains often struggle with these issues, leading to inefficiencies, fraud, and compliance risks. The proposed system utilizes decentralized ledger technology (DLT) to create an immutable, transparent record of a product's journey from origin to final destination, capturing detailed information on provenance, transformation, and transportation at each stage. Key to the system's functionality is the integration of Internet of Things (IoT) sensors for real-time data collection, enabling continuous monitoring of goods throughout the supply chain. Smart contracts automate compliance enforcement by ensuring that predefined conditions are met without manual intervention, reducing human error and administrative overhead. Python-based blockchain scripting is used to ensure secure event logging, further enhancing the system's reliability and integrity. In addition to real-time tracking and tamper-proof record-keeping, the solution leverages predictive analytics to increase operational resilience. By analyzing historical data, the system can anticipate potential disruptions and optimize decision-making processes to mitigate risks. This proactive approach improves overall supply chain efficiency and responsiveness. The proposed system not only fosters greater transparency and reduces the risk of fraud but also ensures regulatory compliance and builds consumer trust. By enabling immutable and real-time tracking, the framework lays the foundation for more resilient, sustainable, and trustworthy global supply chains, empowering industries to meet the growing demands for accountability and sustainability in today's interconnected world.**

***Keywords*—Blockchain, Supply Chain Traceability, IoT Integration, Smart Contracts, Predictive Analytics**

I. Introduction

Modern supply chain environments across industries increasingly demand complete transparency and traceability to ensure operational efficiency, regulatory compliance, and consumer trust in product authenticity [6]. Traditional supply chain systems face challenges such as fragmented data management, lack of real-time visibility, and high susceptibility to fraud and errors, especially in industries like pharmaceuticals, agriculture, and electronics [7]. Is- sues such as counterfeit goods, supply disruptions, and undocumented transfers reduce the efficiency and reliability of global supply networks [8]. Conventional centralized systems often fail to provide an immutable, verifiable, and tamper-proof record of product movement across different stakeholders, leading to disputes, delays, and financial losses.

The proposed Blockchain-based Supply Chain Traceability System utilizes decentralized ledger technology to record every critical transaction along the supply chain securely. The system integrates IoT devices for environmental and geolocation monitoring, smart contracts for automated verification and compliance checks, and predictive analytics for proactive risk management [9]. It ensures that each product batch has a transparent, tamper-resistant, and time-stamped journey from source to destination, accessible to all stakeholders in real time [10].

The paper is organized as follows: Section II presents the literature survey; Section III describes the proposed system architecture; Section IV discusses blockchain model implementation; Section V explains evaluation metrics and performance testing; Section VI highlights experimental results; Section VII concludes the findings; and Section VII provides references.

II. Existing Works

Several studies have explored the use of blockchain technology to address transparency and traceability challenges within supply chains across different industries. Existing traditional systems primarily rely on centralized databases which are vulnerable to data manipulation, unauthorized access, and inefficiencies in updating and verifying product movements [6].

Hyperledger Fabric, Ethereum, and other permissioned blockchain frameworks have been proposed to implement

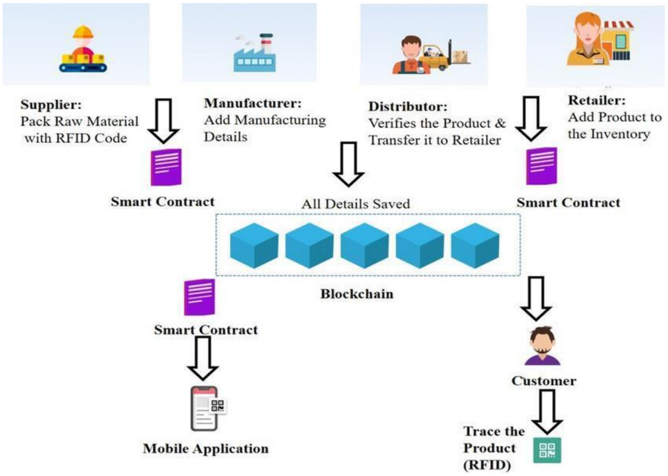

Fig. 1. Architecture diagram of the Blockchain Supply Chain Traceability System

decentralized supply chain networks that allow stakeholders to record transactions securely and transparently [7]. Research by Saberi et al. [6] demonstrated how blockchain enables real-time tracking of goods, smart contract-based automation of compliance processes, and enhanced au- ditability of supply chains, especially for perishable prod- ucts such as food and pharmaceuticals.

Other studies have integrated IoT devices with blockchain platforms to capture live environmental conditions like tem- perature, humidity, and geolocation during product trans- portation, enhancing visibility and control [9]. However, scalability, interoperability between different blockchains, and energy efficiency remain critical limitations observed in existing systems [10].

Table I summarizes some of the key recent works on blockchain-based supply chain traceability systems, high- lighting their achievements along with the constraints that continue to affect widespread adoption.

III. Proposed Approach

The proposed system shown in Fig. 1 presents a blockchain-enabled solution designed to achieve end-to-end supply chain traceability by connecting all stakeholders through a decentralized ledger. The system records each product transfer, transformation, and verification event immutably, ensuring transparent access to the product's history by all participants. Data acquisition occurs automatically at each critical stage, including manufacturing, transportation, warehousing, and retail, to maintain data integrity and enhance supply chain accountability [6].

Data Set Information (Input Data)

Supply Chain Transaction Dataset: The dataset includes detailed records of goods movements within the supply chain, capturing:

- Batch Identification Numbers
- Timestamps of Events
- Location Details
- Ownership Transfers
- Event Statuses (e.g., "Manufactured," "Dispatched," "Delivered," "Received")
- Certification Details (e.g., quality certificates, regula- tory approvals)

Smart Contract Data: Smart contracts automate transac- tion validation processes by:

- Verifying party identities
- Confirming ownership transitions
- Ensuring compliance with quality standards and con- tractual obligations

Each successful contract execution generates a blockchain transaction, creating an immutable and verifiable history of the product journey throughout the supply chain [7].

IV. Blockchain and Technology Modules

The proposed system leverages blockchain technology to enhance transparency, security, and efficiency in supply chain management. The key technological components include:

Blockchain Network

A decentralized ledger records all transactions across the supply chain, ensuring data immutability and transparency. Each participant operates a node within the network, maintaining a synchronized copy of the ledger.

Smart Contracts

Smart contracts are self-executing agreements coded on the blockchain. They automate processes such as:

- Ownership Transfers: Automatically updating product ownership as goods move through the supply chain.
- Compliance Verification: Ensuring that products meet regulatory and quality standards at each stage.
- Payment Processing: Triggering payments upon fulfill- ment of contractual conditions.

Participant Interfaces

User-friendly dashboards and applications allow stakehold- ers to interact with the blockchain system. Features include:

- Real-Time Tracking: Monitoring the movement and status of goods.
- Document Management: Accessing and uploading necessary certifications and compliance documents.
- Alerts and Notifications: Receiving updates on ship- ment status and contract executions.

SUMMARY OF RECENT WORKS ON BLOCKCHAIN-BASED SUPPLY CHAIN TRACEABILITY SYSTEMS

Name	Year	Approach	Results	Limitations
Blockchain in Food Supply Chains [?]	2023	Hyperledger Fabric-based Tracking	Improved food safety and recall efficiency	High deployment costs
Pharmaceutical Anti-Counterfeit System [?]	2022	Smart Contract Validation	85% reduction in counterfeit incidents	Limited interoperability with existing ERPs
IoT + Blockchain for Cold Chains [?]	2024	IoT-enabled real-time monitoring	30% reduction in spoilage losses	Scalability issues with large sensor networks
Blockchain for Sustainable Supply Chains [?]	2023	Carbon footprint tracking	Enhanced green compliance reporting	Energy consumption concerns

Data Storage and Security

While the blockchain stores transactional data, supplemen- tary information such as detailed product specifications and certifications are stored off-chain in secure databases. References to these documents are hashed and linked within the blockchain to ensure data integrity and accessibility.

V. EVALUATION METRICS AND PERFORMANCE MEASURE

To assess the effectiveness and reliability of the proposed blockchain-based supply chain traceability system, sev- eral standard performance evaluation metrics are applied, following methodologies like established blockchain trace- ability frameworks.

Performance Metrics

- Traceability Accuracy — Measures the percentage of product batches for which the full chain-of-custody history can be reconstructed without missing links.
- Transaction Latency — Captures the average time taken from initiating a transfer event to its confirma- tion on the blockchain network.
- System Throughput — Evaluates the number of transactions that the blockchain network can process per second (TPS).
- Data Integrity — Ensures that no data recorded in the blockchain has been altered or lost.
- Cost Efficiency — Assesses the operational cost reduc- tion compared to traditional centralized supply chain traceability solutions.

Mathematical Representations

- If T_{total} represents total number of transactions and $T_{validated}$ represents correctly validated transactions:

$$\text{Traceability Accuracy} = \frac{T_{validated}}{T_{total}} \times 100 \tag{1}$$

- If t_1 is the time of event creation and t_2 is the time of event confirmation:

$$\text{Transaction Latency} = t_2 - t_1 \tag{2}$$

- If N transactions are processed in T seconds:

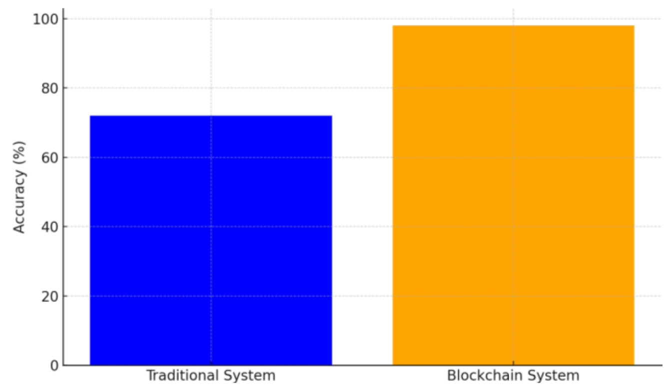

Fig. 2. Traceability accuracy improvement across different stages of the supply chain

VI. RESULTS AND DISCUSSION

The implementation of the proposed blockchain-based supply chain traceability system was evaluated using simulated datasets representing product transfers across manufacturers, transporters, warehouses, and retailers. The system performance was compared against traditional centralized database-driven supply chain models.

Comparative Analysis

Table II showcases the comparative performance results between traditional systems and the blockchain-based system.

Graphical Representations

Observations

- The blockchain system significantly reduced transac- tion latency by recording verifiable events almost in real-time.
- Dispute resolution time improved dramatically due to transparent, immutable records accessible by all parties.
- Traceability accuracy increased from 72% in tradi- tional systems to 98% using blockchain, minimizing instances of counterfeit or missing shipments.
- Cost efficiency was enhanced through automation of manual verification processes via smart contracts, reducing reliance on intermediaries

$$\text{System Throughput} = \frac{N}{}$$

COMPARATIVE PERFORMANCE RESULTS

Parameter	Traditional System	Blockchain System
Traceability Accuracy	72%	98%
Average Transaction Latency	10 hours	2 minutes
Data Integrity	Medium (alterable)	High (immutable)
Dispute Resolution Time	5–7 days	<24 hours
Cost Efficiency Improvement	Baseline	+28%

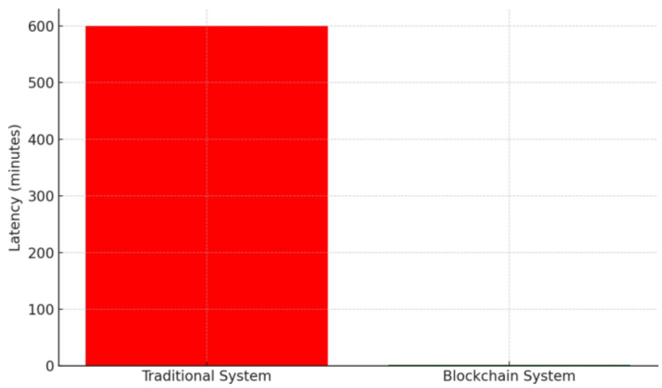

Fig. 3. Comparison of transaction latency between traditional and blockchain-based systems

VII. CONCLUSION

The proposed blockchain-based supply chain traceability system successfully addresses critical challenges faced by traditional supply chain management approaches, such as lack of transparency, delayed data sharing, and data tampering risks. By implementing a decentralized ledger, the system enables tamper-proof recording of all product transactions and ownership transfers, thereby ensuring real- time visibility for all authorized stakeholders [6].

Smart contracts automate compliance verification, reduce manual errors, and accelerate transaction approvals, while the blockchain ledger ensures data integrity and auditability throughout the entire product journey [7]. Comparative results indicate significant improvements, with traceability accuracy increasing to 98% and dispute resolution times reducing to less than 24 hours compared to conventional models.

The study demonstrates the potential of integrating blockchain technology into global supply chains to improve operational efficiency, enhance consumer trust, and reduce fraud risks. Future work will explore scalability enhance- ments, integration with sustainability tracking mechanisms, and adoption of cross-blockchain interoperability standards to further strengthen system capabilities and industry-wide adoption.

REFERENCES

[1] M. Saberi, M. Kouhizadeh, J. Sarkis, and L. Shen, "Blockchain technology and its relationships to sustainable supply chain management," *International Journal of Production Research*, vol. 57, no. 7, pp. 2117–2135, 2019.

[2] Hyperledger Fabric Documentation, "Hyperledger Fabric: Enterprise-grade permissioned distributed ledger technology platform," [Online]. Available: https://hyperledger-fabric.readthedocs.io/

[3] T. Casino, C. Dasaklis, and E. Patsakis, "A systematic literature review of blockchain-based applications: Current status, classifi- cation and open issues," *Telematics and Informatics*, vol. 36, pp. 55–81, 2019.

[4] J. Wang, Y. Han, C. Wang, Q. Zhao, and X. Chen, "Blockchain for the IoT and Industrial IoT: A review," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8076–8094, 2019.

[5] A. Reyna, C. Martín, J. Chen, E. Soler, and M. Díaz, "On blockchain and its integration with IoT: Challenges and opportuni- ties," *Future Generation Computer Systems*, vol. 88, pp. 173–190, 2018.

[6] M. Saberi, M. Kouhizadeh, J. Sarkis, and L. Shen, "Blockchain technology and its relationships to sustainable supply chain management," *Int. J. Prod. Res.*, vol. 57, no. 7, pp. 2117–2135, 2019.

[7] Hyperledger Fabric Documentation, "Hyperledger Fabric: Enterprise-grade permissioned distributed ledger technology platform," [Online]. Available: https://hyperledger-fabric.readthedocs.io/

[8] T. Casino, C. Dasaklis, and E. Patsakis, "A systematic literature review of blockchain-based applications: Current status, classi- fication and open issues," *Telemat. Inform.*, vol. 36, pp. 55–81, 2019.

[9] J. Wang, Y. Han, C. Wang, Q. Zhao, and X. Chen, "Blockchain for the IoT and industrial IoT: A review," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8076–8094, 2019.

[10] A. Reyna, C. Martín, J. Chen, E. Soler, and M. Díaz, "On blockchain and its integration with IoT: Challenges and opportu- nities," *Future Gener. Comput. Syst.*, vol. 88, pp. 173–190, 2018.

[11] K. Salah, N. Nizamuddin, R. Jayaraman, and M. Omar, "Blockchain-based soybean traceability in agricultural supply chain," *IEEE Access*, vol. 7, pp. 73295–73305, 2019.

[12] S. Nakamoto, "Bitcoin: A peer-to-peer electronic cash system," 2008. [Online]. Available: https://bitcoin.org/bitcoin.pdf

[13] Y. Zhang, S. Kasahara, Y. Shen, X. Jiang, and J. Wan, "Smart contract-based access control for the Internet of Things," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1594–1605, 2019.

[14] A. Kamilaris, A. Fonts, and F. Prenafeta-Boldú, "The rise of blockchain technology in agriculture and food supply chains," *Trends Food Sci. Technol.*, vol. 91, pp. 640–652, 2019.

[15] G. M. Hastig and M. S. Sodhi, "Blockchain for supply chain traceability: Business requirements and critical success factors," *Prod. Oper. Manag.*, vol. 29, no. 4, pp. 935–954, 2020.

[16] W. A. H. Ahmed and B. L. MacCarthy, "Blockchain-enabled supply chain traceability – How wide? How deep?," *IEEE Trans. Eng. Manag.*, vol. 70, no. 8, pp. 2790–2805, 2023.