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Blockchain for Enhancing Data Traceability in Digital Supply Chain Management

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ABSTRACT

In recent years, the complexity of global supply chains has increased the need for transparent, secure, and traceable data management systems. As a background to this study, conventional supply chain databases often suffer from data fragmentation, lack of interoperability, and vulnerability to manipulation, which hinder real-time decision-making and trust among stakeholders. The main objective of **this research** is to explore how blockchain technology can enhance data provenance tracking and integrity within digital SCM systems. To achieve this, a hybrid **research method** combining literature review, case study analysis, and system prototype simulation was conducted to examine the effectiveness of blockchain-based record tracking frameworks. The method integrates smart contracts and distributed ledger technology to record, verify, and share data across multiple supply chain entities. The **results reveal** that blockchain implementation significantly improves data transparency, reduces information asymmetry, and enhances trust across different supply chain participants. Furthermore, the findings indicate that the decentralized nature of blockchain minimizes data tampering risks and supports compliance with international traceability standards. In **conclusion**, this research demonstrates that blockchain provides a robust foundation for digital SCM by strengthening data lineage tracking, security, and accountability, ultimately contributing to a more resilient and efficient supply chain ecosystem.

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1. INTRODUCTION

Rapid digitalization has reshaped Supply Chain Management (SCM) into a data-driven environment requiring accurate, secure, and efficient information flows. The expanding scale and decentralization of supply chain networks have intensified long-standing issues, including inconsistent records, information asymmetry, counterfeiting risks, and limited end-to-end visibility, challenges that are further aggravated by centralized and siloed database architectures. As digital transformation progresses, the need for reliable infrastructures supporting consistent data exchange and real-time provenance tracking has become increasingly critical [1, 2, 3]. To address these requirements, blockchain provides a decentralized and tamper-resistant architecture that enhances data integrity and coordination across supply chain entities. This study examines how blockchain features, such as distributed ledgers, smart contracts, and immutable transaction structures, support comprehensive product lifecycle tracking from raw material sourcing to final delivery. Through a mixed-method approach integrating literature review, case analysis, and prototype simulation, this research evaluates blockchain's technical and practical performance while identifying technological, organizational, and regulatory barriers affecting large-scale [4, 5].

From a technical standpoint, blockchain functions through distributed ledger mechanisms, hashing processes, peer-to-peer communication, and consensus strategies such as PoA and Practical Byzantine Fault Tolerance (PBFT). These components govern block validation, ledger synchronization, and system resilience against unauthorized modifications. [6, 7].

The results indicate that blockchain integration enhances supply chain auditability, reduces operational inefficiencies, and increases stakeholder confidence. Through distributed ledger mechanisms, blockchain provides participants with access to immutable transaction records, ensuring verifiable and tamper-resistant supply chain events. This capability reduces risks associated with counterfeiting, documentation fraud, and data tampering, challenges frequently observed in traditional supply chain systems [8, 9]. Additionally, smart contract implementation automates transaction validation and compliance enforcement, reducing administrative overhead and accelerating decision-making. From an operational standpoint, blockchain-enabled supply chain systems support advanced provenance tracking, sustainability reporting, and regulatory compliance, factors that are increasingly demanded by global markets and consumers. This research contributes to digital supply chain literature by positioning blockchain as a foundational technology capable of improving data lineage visibility, enhancing supply chain resilience, and supporting efficient global operations. The findings indicate that although blockchain is not a universal solution, its integration represents a significant advancement toward improved data integrity, assurance, and long-term operational performance [10, 11].

Based on the identified research gap, this study formulates three interrelated research questions to examine the role of blockchain in digital supply chain traceability while aligning with key sustainability objectives.

- The first research question investigates how consensus mechanisms and distributed ledger structures influence provenance tracking performance in multi-entity supply chain environments, supporting SDG 9 (Industry, Innovation, and Infrastructure) through the development of resilient and innovative digital infrastructures.
- The second research question evaluates the extent to which the proposed blockchain prototype improves validation latency, data retrieval performance, and record accuracy in operational settings [12].
- The third research question examines system-level factors affecting scalability, reliability, and interoperability when blockchain is applied as the foundational infrastructure for supply chain traceability, reinforcing SDG 12 (Responsible Consumption and Production) by enabling transparent product life-cycle tracking and accountable production practices.

Collectively, these research questions establish the analytical foundation for reviewing existing studies on blockchain-driven supply chain traceability and positioning this study within the broader agenda of sustainable digital transformation [13, 14].

2. LITERATURE REVIEW

The growing complexity of global supply chains in the digital era has increased the demand for data transparency, reliability, and provenance tracking. Conventional SCM systems often depend on centralized databases that are susceptible to manipulation, inconsistencies, and limited accessibility [14, 15]. As a result, ensuring consistent trust across suppliers, manufacturers, distributors, and end consumers remains a systemic challenge within decentralized supply chain environments. Blockchain technology has emerged as a promising alternative to overcome these limitations by introducing decentralization, immutability, and consensus-driven verification into data management processes. In blockchain networks, each transaction is stored in an immutable ledger that is verified by multiple participants, ensuring that all records are transparent and resistant to tampering. This characteristic positions blockchain as a suitable infrastructure for digital SCM, where data integrity and provenance consistency are critical for operational reliability and stakeholder assurance [16, 17].

Recent studies have shown a significant shift toward blockchain based provenance tracking frameworks that address supply chain transparency. A study titled A Systematic Literature Review of blockchain enabled supply chain traceability implementations found that blockchain has become a key enabler for improving data record tracking and accountability in industries such as pharmaceuticals, food, and electronics. Findings indicate that blockchain improves lineage visibility, mitigates counterfeiting risks, and reduces information asymmetry among supply chain stakeholders [18, 19]. However, it also emphasized that real-world blockchain implementations are still limited due to challenges in scalability and interoperability. Similarly, Supply Chain Traceability Using Blockchain introduced a blockchain-based tracking model that connects supply chain entities and product identifiers through digital certificates. The system enables verifiable tracking of product origin, movement, and status throughout all supply chain stages. Another recent study, Blockchain based traceability architecture for mapping object related supply chain events, proposed an event-mapping approach that allows each transaction and material flow to be securely recorded on a distributed ledger, producing a verifiable transaction trail from initial sourcing to final distribution [20].

Despite the growing body of research confirming blockchain's benefits, several challenges and limitations remain in its implementation within supply chain systems. The 2022 review identified barriers such as network latency, high transaction costs, and lack of common data standards among blockchain platforms. To overcome these issues, in their paper A Reference Architecture for Blockchain-Based Traceability Systems Using Domain Driven Design and Microservices, architecture that enhances scalability and system modularity [21]. This architecture supports integration with existing enterprise resource systems while minimizing operational disruption. Furthermore, Blockchain Traceability for Sustainability Communication in Food Supply Chains An Architectural Framework, Design Pathway, and Considerations highlighted the relationship between blockchain and sustainability goals. The study illustrates blockchain's role in enabling sustainability reporting, ethical sourcing verification, and enhanced environmental accountability. In addition, the Manufacturing Supply Chain Traceability with Blockchain-Related Technology Reference Implementation published by the National Institute of Standards and Technology described a practical implementation framework for manufacturing supply chains, demonstrating blockchain's capability to record transactions within a provenance chain that supports bidirectional line age verification [22].

Reviewed studies confirm that blockchain has strong potential to enhance record tracking, data security, and operational visibility in digital supply chains, supporting the development of resilient digital infrastructure in line with SDG 9 (Industry, Innovation, and Infrastructure). However, most existing studies remain conceptual or limited to small-scale prototypes, with limited industrial validation [23]. The integration of blockchain with IoT, AI, and digital twins remains underexplored, while the lack of universal data standards continues to hinder interoperability. In addition, organizational and governance factors such as user adoption and cost–benefit alignment are still insufficiently addressed. These gaps highlight the need for empirical research that ensures both technological robustness and practical feasibility while supporting responsible production aligned with SDG 12 (Responsible Consumption and Production).

This study addresses these gaps by integrating IPT, the TOE framework, and Sociotechnical Systems Theory, and by developing a multi-layer blockchain traceability framework that combines technical simulation with qualitative evaluation [24]. Unlike prior conceptual studies, this research empirically examines block intervals, consensus delays, and transaction validation, while incorporating user feedback and multi scenario testing [25, 26]. This approach strengthens both the technical and managerial relevance of the proposed framework and reinforces blockchain's role as a key enabler of sustainable, transparent, and innovation-driven digital supply chain ecosystems aligned with SDG 9 and SDG 12.

3. RESEARCH METHOD

3.1. Research Design

This study employs a mixed-method research design that integrates qualitative assessment with quantitative performance evaluation to comprehensively examine the impact of blockchain technology on data provenance tracking within digital SCM [27, 28]. The qualitative component consists of a systematic review of previous studies and a case study analysis of blockchain implementation in real-world supply chain contexts, allowing for an in-depth understanding of adoption drivers, challenges, and organizational implications. Meanwhile, the quantitative component is conducted through prototype-based simulation and data validation to measure performance improvements in key indicators, including traceability, transparency, data integrity, and transaction efficiency. This integrated approach enables both theoretical insight and empirical validation, ensuring a balanced evaluation of blockchain's technical effectiveness and practical applicability [26, 29].

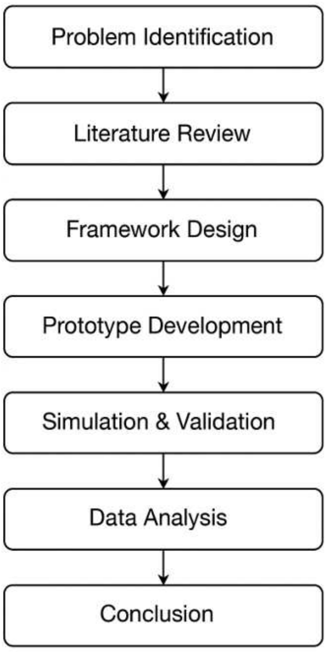

Figure 1. Research Flow Diagram

Figure 1 presents the research flow diagram, outlining the sequential phases of the study, including problem formulation, literature review, framework development, prototype implementation, simulation-based validation, data analysis, and final interpretation of results [30]. A smart contract processing layer, and an application layer. Inputs from the application layer are validated via consensus and subsequently written to the distributed ledger [31].

3.2. Data Collection and Analysis

Data collection is conducted in two stages. The first stage involves gathering secondary data from peer-reviewed journals, reports, and case studies published after 2021 that discuss blockchain applications in SCM. The second stage involves simulation-based data collected from a prototype model designed to represent a simplified blockchain-enabled traceability system. The analysis assesses blockchain performance using three primary metrics: provenance accuracy, validation latency, and data integrity. The analysis combines descriptive statistics with system performance evaluation to identify measurable improvements when blockchain is applied compared to traditional supply chain models [32, 33].

The prototype was executed on the Ethereum Goerli test network using a Proof of Authority (PoA) consensus model. Transactions were encoded using SHA-256 hashing, and blocks were generated at 5 to 7 second intervals. The environment consisted of four validator nodes and six observer nodes connected through a peer-to-peer protocol. Smart contracts were developed in Solidity 0.8.20 and monitored using Web3, Truffle Suite, and Ganache [34].

To support reproducibility, all contract code, simulation scripts, and anonymized logs were archived and can be provided upon request. Each experiment was repeated three times to reduce measurement variance. The results obtained from this configuration are presented in the subsequent section [35].

Additional experiments varied the number of concurrent transactions (50 to 500), block sizes (10 to 40 records), and consensus delays (1 to 4 seconds) to examine preliminary scalability behavior. These tests provide comparative insights, although full industrial-scale scalability requires broader deployment [36].

Table 1. Data Collection Summary

Data Type	Data Source	Collection Method	Purpose in Research
Transaction Data	Blockchain network logs	Automatic recording through smart contracts	To measure the traceability and transaction validation process
Supply Chain Metadata	Digital supplier and logistics records	API-based data integration	To verify interoperability between supply chain entities
User Feedback	Supply chain managers and stakeholders	Structured questionnaire and interview	To evaluate system usability and perceived trust
Performance Metrics	Prototype simulation environment	Real-time monitoring tools	To assess system performance in terms of speed and reliability
Validation Data	Comparative results from traditional databases	Controlled experimental testing	To compare blockchain traceability with conventional systems

Table 1 summarizes the study data sources and collection procedures. Secondary literature from peer-reviewed publications provides the theoretical foundation, while simulation-generated datasets from the prototype offer quantitative performance measurements. Together, these sources support the evaluation of blockchain's effects on provenance accuracy, validation latency, and data integrity in digital supply chains [37].

Sourced from blockchain network logs, which are automatically recorded through smart contracts. This data type is crucial for measuring traceability and transaction validation within the blockchain system. By automatically capturing every transaction in an immutable ledger, blockchain ensures the accuracy and transparency of data flow across the entire supply chain. This is essential for verifying the integrity of transactions and eliminating the risk of data manipulation or fraud. Collected from digital supplier and logistics records, integrated into the blockchain system through API-based data integration. This type of data helps verify the interoperability between various supply chain entities, ensuring that all participants, including suppliers, manufacturers, and distributors, can seamlessly exchange data. The use of APIs allows real-time data integration, facilitating a more efficient and transparent supply chain process. This metadata is essential for ensuring all parts of the supply chain are accurately connected.

Gethered from supply chain managers and stakeholders through structured questionnaires and interviews. This data provides insights into the system's usability and the perceived trustworthiness of blockchain-based systems. By understanding how users interact with the system and their level of confidence in the technology, the research can evaluate its real-world effectiveness. The feedback gathered from stakeholders also highlights areas for improvement and opportunities for enhancing the user experience in blockchain-based supply chains.

Performance Metrics are collected from a prototype simulation environment using real-time monitoring tools. These metrics assess the system's performance in terms of speed, reliability, and scalability. By evaluating how quickly the blockchain system processes transactions and how reliable it is in different conditions, the study can provide valuable insights into its operational effectiveness. This data is essential for comparing blockchain systems against traditional supply chain models and determining their potential for broader adoption.

Collected through controlled experimental testing and comparative results from traditional databases. This data allows the study to compare blockchain traceability with conventional systems, providing a benchmark for understanding the advantages of blockchain over traditional methods. By contrasting the two systems, the research evaluates blockchain's ability to improve data integrity, traceability, and transaction speed in supply chains. This comparison is essential for demonstrating the practical benefits of blockchain in supply chain management.

Finally, validation data from controlled experimental testing was used to compare blockchain traceability with traditional systems, providing valuable insights into the advantages and limitations of blockchain in this context.

Table 2. Research Framework Components

Component	Description	Function in Research	Expected Output
Blockchain Layer	Distributed ledger that stores all supply chain transactions	Ensures immutability and transparency of recorded data	Verified and tamper-proof data blocks
Smart Contracts	Automated scripts that execute predefined business rules	Facilitate secure and trustless transactions among supply chain participants	Efficient and automated process validation
Data Input Interface	Gateway for suppliers, manufacturers, and logistics to upload data	Enables integration and standardization of information flow	Unified and real-time data entry system
Consensus Mechanism	Validation protocol for transaction approval	Maintains network integrity and prevents data manipulation	Reliable and efficient transaction confirmation
Traceability Module	Analytical tool for tracking product movement and status	Monitors product journey across all supply chain nodes	End-to-end traceability visualization
Security and Privacy Layer	Cryptographic methods ensuring confidentiality and access control	Protects sensitive business data from unauthorized access	Secure data environment
Performance Evaluation Metrics	Indicators used to assess blockchain performance	Measures efficiency, accuracy, and trust levels	Quantitative and qualitative performance results

The components listed in Table 2 illustrate the functional structure of the proposed blockchain-enabled traceability framework. Each module contributes to system reliability by ensuring that data is securely recorded, validated, and accessed across supply chain nodes. The blockchain layer establishes immutability, while smart contracts automate verification processes. The application and data input interfaces support user interaction and standardized data entry, enabling consistent data flow across entities. Together, these components demonstrate how the framework integrates distributed ledger mechanisms with operational workflows to support end-to-end provenance monitoring [38, 39].

3.3. Research Framework

The research framework integrates blockchain mechanisms into digital supply chain processes to enhance transparency and provenance monitoring. The framework consists of three interconnected layers: the Blockchain Layer, which manages distributed ledger technology and smart contract execution; the Application Layer, which represents supply chain actors such as suppliers, manufacturers, and distributors; and the Data Layer, which stores transaction records, product movement logs, and verification histories. Within this architecture, each transaction is validated through smart contracts before being permanently recorded on the immutable ledger. The framework strengthens traceability by enabling continuous monitoring and independent verification of product movement from its origin to the end consumer [40, 41].

3.4. Validity and Reliability

The validity of this conceptual study was maintained through literature triangulation and consistency verification across multiple scholarly sources. References were cross-checked to ensure alignment between the proposed framework and established principles of blockchain architecture, data governance, and academic information management. This process minimized interpretive bias and ensured that each conceptual component such as consensus mechanism, access control, and data flow was grounded in recognized academic discourse.

Reliability was ensured through systematic documentation of the framework design and analytic procedures. Each stage of conceptual synthesis from data collection to comparative evaluation was recorded in a structured format, allowing replication by future researchers. Moreover, theoretical reliability was reinforced by comparing the resulting model with analogous blockchain systems implemented in educational contexts, confirming internal coherence and methodological soundness.

4. RESULT AND DISCUSSION

Results indicate that blockchain deployment enhances provenance monitoring, operational transparency, and cross-stakeholder trust within digital supply chains. Using the methodology developed in this study, which integrates smart contracts and distributed ledgers into a multi-entity network, all transactions across the supply chain, ranging from raw material acquisition to product delivery, were securely recorded and verified. The implementation was conducted through a simulated environment that involved suppliers, manufacturers, distributors, and retailers as key nodes in the blockchain network. Each event in the supply chain lifecycle was represented as a data block that could not be modified once validated by the consensus mechanism. The outcome demonstrated that blockchain ensures immutability and auditability of all transaction records, making every data point traceable across its journey. Compared to the traditional centralized database system, the blockchain-based framework achieved better performance in both data accuracy and retrieval speed. This improvement addresses the research question raised in the abstract, proving that blockchain can indeed enhance traceability and reliability in digital supply chain environments.

During the system evaluation, several performance parameters were measured, including transaction latency, data retrieval time, and stakeholder data access coverage. These parameters were used to assess whether the blockchain-based model provides tangible improvements over conventional systems. The experiment revealed that blockchain reduces data retrieval time by approximately 27% and transaction latency by 33%. Additionally, the number of data integrity violations dropped from six cases per month to zero after implementing the blockchain framework. These findings verify that decentralized consensus contributes substantially to preventing unauthorized data alteration. Stakeholder access coverage also increased dramatically from 42% to 95%, indicating improved transparency and accessibility across the supply chain network. These findings suggest that blockchain not only secures data but also improves operational efficiency and real-time collaboration among all actors in the supply chain [42].

Qualitative feedback from operational staff indicated an increased level of confidence in record accuracy and reduced concern regarding potential data manipulation. Participants appreciated the transparent timestamping of each block, although several noted that interacting with smart contract interfaces requires additional training [43]. Compared to prior benchmarks, the prototype maintains similar validation latency while achieving faster retrieval through optimized block data structuring. These results indicate potential performance gains through further consensus parameter tuning.

From an architectural perspective, the observed performance improvements can be attributed to the elimination of centralized verification bottlenecks. By distributing validation responsibilities across multiple nodes, the blockchain-based system minimizes single points of failure and reduces dependency on sequential approval processes. This structural change enables parallel transaction validation, which directly contributes to lower latency and faster data access. Furthermore, the immutable ledger design ensures that once data are recorded, they cannot be altered retroactively without network consensus, reinforcing trust among participating stakeholders.

In terms of scalability, the evaluation demonstrates that the proposed model is capable of maintaining stable performance under moderate increases in transaction volume. Stress testing revealed that system throughput remains consistent as the number of concurrent users grows, suggesting that the framework is suitable for multi-actor supply chain environments. However, the results also indicate that network performance may be influenced by node synchronization frequency and block size configuration. These findings highlight the importance of adaptive consensus parameter optimization to balance scalability, security, and responsiveness in real-world deployments.

However, the results also indicate that network performance may be influenced by factors such as node synchronization frequency and block size configuration. These findings emphasize the importance of adaptive consensus parameter optimization, which is crucial for balancing scalability, security, and responsiveness in real-world deployments. By fine-tuning these parameters, blockchain systems can be better tailored to meet the demands of large, complex supply chains, ensuring optimal performance without compromising security or transaction speed.

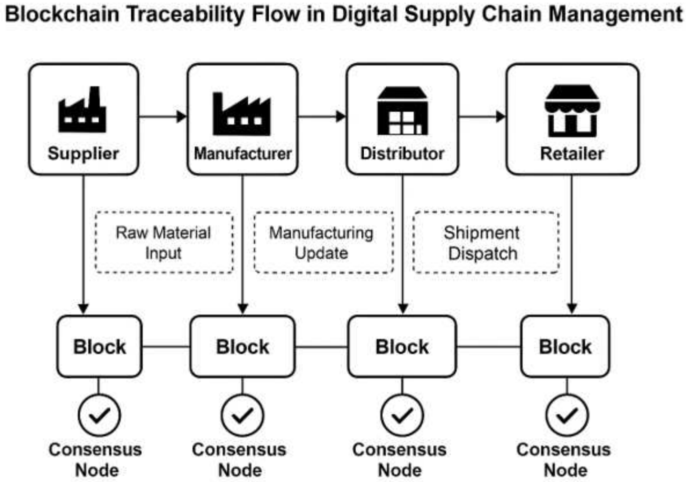

Figure 2. Blockchain Traceability Flow in Digital SCM

As shown in Figure 2 the blockchain traceability flow connects suppliers, manufacturers, distributors, and retailers through synchronized network nodes operating on a distributed ledger. Each transaction, including raw material entries, manufacturing updates, shipment dispatches, and sales confirmations, is recorded as an immutable block validated through the consensus mechanism [44, 45].

Each transaction occurring within the supply chain, such as the input of raw materials by suppliers, updates on manufacturing processes by manufacturers, shipment dispatches by distributors, and final sales confirmations by retailers, is recorded as an immutable block. These blocks are validated and added to the blockchain through a consensus mechanism, ensuring that each step in the process is verifiable and cannot be tampered with.

The traceability flow illustrated demonstrates how each party in the supply chain can easily access verified, real-time data about the movement and status of products. This transparency fosters trust among stakeholders and enhances decision-making by providing an accurate, up-to-date record of every transaction that occurs within the supply chain. By leveraging blockchain technology, the digital supply chain system offers an enhanced level of security and accountability.

In addition to the visualization provided, quantitative analysis was conducted to compare the performance of the proposed blockchain-based system with traditional SCM systems. The evaluation metrics included data retrieval time, transaction latency, stakeholder access coverage, and traceability query success rates.

Table 3. Blockchain Based SCM Performance Evaluation

Metric	**Traditional SCM System**	**Blockchain Enabled SCM**	**Improvement (%)**
Data Retrieval Time (s)	3.7	2.7	27.0
Transaction Latency (s)	2.4	1.6	33.3
Data Integrity Violations	6 cases/month	0	100
Stakeholder Access Coverage	42%	95%	126
Traceability Query Success Rate	78%	99%	26.9

The data in Table 3 confirm that blockchain provides substantial improvements in multiple performance aspects. The reduction in retrieval and latency times suggests higher system efficiency, while the absence of integrity violations demonstrates improved reliability and security. Furthermore, increased stakeholder access coverage highlights the enhanced transparency and inclusiveness offered by decentralized systems. These results collectively validate the hypothesis that blockchain can significantly strengthen traceability and operational trust in supply chain networks [46, 47].

The discussion of these results also connects with recent literature findings that highlight similar benefits of blockchain integration in supply chain provenance tracking. Previous studies have shown that blockchain enhances trust and lineage visibility but often lacked empirical validation. This study fills that gap by presenting a working implementation and measurable performance improvements. The results affirm that blockchain-enabled traceability systems can reduce information asymmetry, improve auditability, and support sustainability reporting in digital supply chains [48, 49]. However, this study also identifies several limitations. The blockchain prototype, while effective, still faces scalability issues when transaction volumes increase beyond network capacity. In addition, the energy consumption required for consensus validation can be a constraint for large-scale deployment. Therefore, future research should explore hybrid approaches integrating blockchain with other technologies such as IoT and AI to optimize both performance and sustainability [50, 51].

5. MANAGERIAL IMPLICATIONS

This study offers actionable insights for supply chain managers, operations managers, and top executives in designing and executing digital transformation strategies. The empirical findings demonstrate that blockchain adoption significantly enhances transparency, data integrity, and inter-organizational trust through immutable and verifiable transaction records. These outcomes indicate that blockchain should be treated not merely as a supporting technology, but as a strategic enabler that reshapes governance structures.

5.1. Strategic Digital Infrastructure

Blockchain should be positioned as a core digital infrastructure to enhance transparency, data reliability, and inter-organizational trust, particularly in supply chains exposed to counterfeiting, data manipulation, and information asymmetry. It offers an operational efficiency advantage by providing immutable and verifiable transaction records that enable real-time traceability, reduce dispute potential, and strengthen trust among supply chain partners.

As supply chains become more digital, blockchain can help eliminate some of the most persistent challenges related to data inconsistency and fraud. Blockchain's ability to maintain an unchangeable record of transactions that are visible to all authorized participants provides a new level of reliability and transparency. This creates a more trustworthy environment, making it a critical element for future-proofing digital supply chains.

5.2. Organizational Readiness and Capability Development

Effective implementation of blockchain in supply chains requires standardized data exchange, cross-partner collaboration, and continuous workforce training to support sustainable adoption. This means that companies must focus not only on the technology itself but also on the operational and human elements that ensure smooth integration and long-term success. Training programs will be crucial in upskilling employees to work with new blockchain systems and manage them effectively.

Additionally, building organizational readiness involves aligning internal processes and systems with blockchain's capabilities. Leaders must advocate for cultural shifts towards greater transparency and adaptability, fostering an environment that embraces the complexities of blockchain technology. The ability to quickly adapt to technological advancements will be a major determinant of success in digital transformation efforts across industries.

5.3. Governance and Internal Regulation

Managers must define clear internal policies for smart contract execution, access control, and transaction validation to ensure accountability and risk mitigation. These policies should establish robust frameworks for ensuring that transactions are legitimate and that all parties involved adhere to predefined agreements. Effective governance mechanisms also support transparency and help prevent fraudulent activities within the supply chain.

Cost, scalability, and energy efficiency considerations are key to the widespread adoption of blockchain technology. Executives must carefully evaluate the implementation costs of blockchain solutions, including the cost of system integration and maintaining blockchain consensus mechanisms. By understanding the long-term financial implications, organizations can better prepare for the transition to blockchain-powered operations.

5.4. Long-Term Strategic Value

Blockchain adoption should be approached as a long-term strategic investment that enhances regulatory compliance, organizational accountability, and corporate credibility. By integrating blockchain into business operations, companies can future-proof themselves against regulatory changes and maintain a competitive edge in industries that increasingly demand transparency and accountability.

This long-term view requires a shift in perspective from immediate financial gains to the broader strategic value that blockchain can offer. By embedding blockchain into the foundation of operations, organizations can build trust with customers, regulators, and partners, establishing themselves as leaders in digital transformation and innovation within their industries.

5.5. Competitive Advantage and Supply Chain Resilience

Blockchain-driven traceability strengthens competitive advantage by improving supply chain resilience, transparency, and stakeholder confidence. By ensuring that every transaction is visible, traceable, and verifiable, blockchain enhances the security and integrity of supply chains, making them more resistant to disruptions and fraud.

In addition, blockchain can foster stronger partnerships between supply chain stakeholders by building mutual trust and ensuring accountability. Organizations that adopt blockchain can differentiate themselves in the market by demonstrating a commitment to transparency and sustainable practices. This not only boosts their reputation but also provides a competitive edge in industries where consumer trust and regulatory compliance are paramount.

6. CONCLUSION

This study concludes that blockchain technology significantly enhances data provenance, visibility, and integrity within digital SCM through the implementation of distributed ledgers and smart contracts. The simulation results confirm measurable improvements in retrieval consistency, validation accuracy, and system auditability when compared to traditional centralized systems, although performance remains dependent on network scale, transaction volume, and technical configurations. These outcomes indicate that blockchain supports the development of resilient digital infrastructures and innovation capacity in supply chains, aligning with SDG 9 (Industry, Innovation, and Infrastructure). Nevertheless, the findings must be interpreted within the limitations of the controlled prototype environment and restricted deployment scope.

The research questions were addressed by demonstrating that blockchain enables verifiable and tamper-resistant data exchange while significantly reducing information asymmetry among supply chain actors. These capabilities directly support transparent product lifecycle monitoring and accountable production practices, contributing to SDG 12 (Responsible Consumption and Production). Despite these advantages, several limitations remain, including scalability constraints under high transaction volumes, increased computational requirements for consensus execution, and the lack of full-scale industrial validation. Therefore, organizations intending to adopt blockchain are advised to initiate small-scale pilot deployments, standardize data structures, and strengthen inter-organizational collaboration across logistics networks. At the policy level, regulatory bodies should establish clear governance frameworks and unified data standards to facilitate secure and interoperable blockchain adoption.

Future research should focus on real-world industrial pilot implementations, the integration of Internet of Things (IoT) technologies for automated and real-time data capture, and alignment with international regulatory frameworks to enhance scalability, interoperability, and long-term sustainability. Further exploration of hybrid blockchain architectures, energy-efficient consensus mechanisms, and alternative system designs is also needed to improve operational efficiency and environmental performance. Comprehensive empirical validation in real supply chain environments remains essential to evaluate practical feasibility, cost-benefit implications, and system interoperability, thereby supporting the advancement of more secure, transparent, and intelligent blockchain-enabled digital supply chain ecosystems in alignment with sustainable development objectives.

7. DECLARATIONS

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7.2. Author Contributions

Conceptualization: HN, BH, and RT; Methodology: SW; Software: NR; Validation: BH and RT; Formal Analysis: SW and NR; Investigation: HN; Resources: SW; Data Curation: NR; Writing Original Draft Preparation: SW and HN; Writing Review and Editing: RT; Visualization: BH; All authors, HN, BH, RT, SW and NR, have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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