Blockchain Technology and Its Impact on Transparency, Security, and Efficiency in Supply Chain Management

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Abstract

Background: The length and depth of global supply networks have been rising over time, causing permanent problems in visibility, protection, and performance. Blockchain technology has come out as a disruptive technology to tackle all these problems, by providing decentralized, safe and transparent systems.

Objective: This article examines the use of blockchain technology within the context of supply chain and specifically digs deeper into the area of increased transparency, security and subsequent efficient supply chain transactions. The aim is to show that it is possible to transform resource supply chain operations through blockchain and engender trust amongst stakeholders.

Methods: Permissioned blockchain system has been design and implemented using proof of Authority (PoA) consensus algorithm. IoT sensors were deployed to obtain data in real-time, and smart contracts were incorporated to perform the tasks of product evaluation, and payment authorization. The performance of the system was assessed depending on the indicators including the number of transactions per time or volume per time, time taken for each transaction, auditability and workability.

Results: The combination of high transaction throughput with low latency made the blockchain system scalable as well as operationally stable. Smart contracts were able to minimize the time taken and mistakes, and improve the integration of IoT in relation to tracing transactions in real time. The system also proved that it had the ability to withstand cyber assaults and no data were compromised.

Conclusion: Based on the analysis of supply chain problems, blockchain technology can be used to transform supply chain management. Furthermore, more studies should be done on the future compatibility of the usage of such a system with new technology trends and also its implementation in multiple regions supply chain to harness this valuable system.

Keywords: Blockchain, supply chain management, transparency, security, traceability, smart contracts, decentralized, scalability, data integrity, SCM (Supply Chain Management)

1. Introduction

Over the past decade, the complexity of supply chain networks has significantly expanded due to the forces driving globalization, leading to transparency, cybersecurity issues, and operational challenges. These problems intensify with the growing complexity of interdependent systems, resulting in risks and distrust within the environment. Recent innovations in technological solutions, especially blockchain technology, have attracted academic and industrial interest in addressing these issues. Blockchain's application to supply chain management (SCM) leverages decentralized, immutable, and transparent records that enable real-time tracking of activities across industries (Moosavi et al. 2021; Park and Li 2021). This article explores various ways blockchain impacts SCM and highlights its potential in resolving these challenges.

Considerable research has been conducted on blockchain technology's implications in SCM. Moosavi et al. (2021) provided a general discussion on the advantages of blockchain in enhancing supply chain transparency (Moosavi et al. 2021). Similarly, Dasaklis et al. (2022) examined the technology's application in increasing traceability at various supply chain stages, crucial for product identification and accountability (Dasaklis et al. 2022). Brookbanks and Parry (2022) investigated blockchain's utility in fostering confidence within existing relationships, such as the wine supply chain, demonstrating its potential to stabilize stakeholder relationships (Brookbanks 2022). In the realm of cybersecurity, Bayramova et al. (2021) argued that blockchain could enhance supply chain resilience against cyber risks through an effective data protection system (Bayramova, Edwards, and Roberts 2021).

Despite these studies highlighting blockchain's prospects, the literature still exhibits certain shortcomings. While significant emphasis has been placed on blockchain's advantages for supply chain transparency and effectiveness, limited research has explored its integration with IoT and AI for real-time monitoring and data analysis in SCM (Van Nguyen et al. 2023). Furthermore, concerns regarding scalability, adoption barriers, and regulatory compliance remain inadequately addressed in strategic discussions (Kouhizadeh, Saberi, and Sarkis 2021; Liu 2021). Additionally, although several papers focus on blockchain applications in sectors like healthcare, agriculture, and transportation, few studies compare its performance across these industries (Agrawal et al. 2023; Omar et al. 2021). These gaps present opportunities to explore the potential for extending and scaling blockchain applications in supply chains to other fields (Qasim et al. 2024).

This study aims to fill these gaps by proposing a framework that outlines how blockchain affects transparency, security, and efficiency in SCM. Unlike previous research, this paper integrates insights from various fields to analyze how the convergence of blockchain with IoT and AI technologies enhances supply chain flexibility and robustness (Yousif et al. 2024). Additionally, the article addresses potential issues related to blockchain adoption and application, offering solutions to these challenges through appropriate frameworks and regulations (Qasim, Rahim, and Bodnar 2024). The originality of this study lies in its combination of multiple research areas and its focus on comparative performance assessment, thus contributing to the understanding of blockchain's applicability in diverse supply chain environments.

This article employs a methodological approach that incorporates both qualitative and quantitative research methodologies to evaluate blockchain's contribution to SCM. This approach includes examining real-life blockchain applications across various industries, conducting a brief literature review, and performing an empirical analysis of blockchain's performance on metrics such as transparency and cybersecurity (Qasim et al. 2021). Various analytical methods, including comparative performance modeling and thematic data analysis, will be utilized to analyze data from different sources. The primary objective of this research is to provide an overview of how blockchain technology can transform SCM. Specifically, it aims to understand blockchain's efficiency in enhancing supply chain transparency, security, and productivity, discuss its interaction with IoT and AI for continuous monitoring and prediction, describe strategies to overcome key adoption barriers and scalability limitations, and compare blockchain's effectiveness across different industries. By achieving these objectives, this research will foster academic discussions on blockchain technology in SCM and offer practical recommendations for practitioners. The expected outcomes include enhancing knowledge of blockchain's possibilities, recommending concrete implementation steps, and proposing further research in blockchain technology, a rapidly developing field.

1.1. The Aim of the Article

This article aims to investigate and discuss the innovative characteristics of blockchain technology in SCM, focusing on its potential to enhance transparency, security, and efficiency. Supply chain processes have become increasingly sophisticated, globalized, and complex, necessitating better tracking systems, data quality assurance, and improved performance. Standard supply chain environments typically employ command and control structures that stifle innovation, expose supply chains to fraud, and limit real-time data sharing. These issues are particularly significant in industries such as pharmaceuticals, food, and electronics, where forgery and threats to life pose significant risks to the population.

The primary focus of this article is to provide a comprehensive analysis of how blockchain, as a decentralized and immutable ledger, can address these challenges. Blockchain technology, which ensures an unchangeable record of all actions performed on products and their circulation, can enhance trust among supply chain members, eliminate instances of fraud and counterfeit products, and integrate smart contracts into the supply chain process.

Additionally, this paper discusses how blockchain can be utilized to achieve higher security by removing single points of failure and reducing the likelihood of cybercriminals succeeding. This is made possible through consensus mechanisms that make unauthorized tampering of data almost impossible, thereby making the entire supply chain data more reliable.

However, this article will also examine concerns and weaknesses associated with the application of blockchain in SCM, such as scalability considerations, regulatory issues, and the cost implications of deploying blockchain technology. To support the proposed conceptual framework, this article systematically reviews both theoretical and empirical research on blockchain-enabled SCM, aiming to present a comprehensive analysis of how blockchain can be used to manage supply chain networks within and across industries. By identifying these factors, the article seeks to contribute to the body of knowledge on how blockchain can drive supply chain innovation.

1.2. Problem Statement

SCM continues to suffer from numerous issues, including the production of substandard goods, lack of transparency, and systemic flaws, particularly in industries concerned with product quality and origin. The centralized database approach of enterprise SCM systems and the reliance on paper-based documentation have proven inadequate in meeting the Balanced Scorecard (BSC) needs of organizations. These systems are often duplicated and isolated, making them more susceptible to data alteration, errors, and slow processing compared to real-time application processing. This results in reduced productivity and exposes the supply chain to risks such as fraud and counterfeiting, especially in contexts involving multiple cross-border transactions where products are sold several times across different countries, leading to partially transparent data.

Despite fulfilling certain essential preconditions, the issue of security remains unresolved. Most business data are stored in centralized repositories, rendering companies vulnerable to cyber risks. The loss of data typically includes vital product parameters, shipment schedules, and payment information, among other critical details. Additionally, there is a lack of timely control over supply chain processes, as stakeholders often rely on outdated information, causing congestion and delays over time. These systems do not support real-time product authentication, posing significant risks for sensitive industries such as pharmaceuticals and food, where counterfeit products can have serious consequences.

Given these challenges, there is a pressing need for a more secure, reliable, and efficient system. Conventional approaches to documenting supply chain data have been plagued by these issues, but blockchain technology offers a potential solution. However, its application is not yet widespread, and many industries still face challenges in implementing blockchain technology. Therefore, this article aims to explore how blockchain can be applied at all stages of SCM to address issues related to transparency, security, and efficiency.

2. Literature Review

Blockchain technology has been extensively discussed and implemented in SCM to address issues of opacity, data security, growth, and workflow inefficiencies. However, as suggested in the literature analysis presented above, this stream of research entails substantial concerns and limitations that need to be resolved in the future to enable the growth of significant applications of blockchain technology in practice.

Transparency is one of the benefits that blockchain offers in supply chain systems. According to Kowalski and Esposito (2023), blockchain establishes fixed blocks of information, adding credibility for stakeholders in European supply chains (Kowalski and Esposito 2023). Nevertheless, their work primarily addresses theoretical advantages and overlooks practical implementation issues such as system compatibility and regional regulations. Similarly, Della Valle and Oliver (2021) demonstrate how a blockchain-based data platform enhances information sharing in supply chain networks (Della Valle and Oliver 2021). However, they fail to recognize the critical importance of data integration across various systems and backgrounds to support such processes. These issues highlight the need for studies with agile blockchain design and the application of common middleware interfaces to facilitate technology integration under diverse conditions (Hashim and Al-Sul 2021).

Security continues to be a necessity for contemporary SCM systems. Liu et al.(2023) describe an approach to constructing a secure blockchain that minimizes security problems through enhanced encryption (Liu et al. 2023). Although successful, their strategy introduces additional complexity, increasing computational demands and posing limitations in constrained environments. Similarly, Abidi et al.(2021) enhance secure information sharing using data sanitization processes, but they do not comprehensively address insider threats or unauthorized access (Abidi et al. 2021). This suggests a need for lighter cryptographic solutions and improved access control, possibly including machine learning for real-time anomaly detection.

Addressing security in supply chain management blockchain applications remains elusive. Sarfaraz et al.(2022) propose a scheme for a scalable permissioned blockchain suitable for large-scale business environments (Sarfaraz, Chakrabortty, and Essam 2022). However, they did not comprehensively test their framework under high-traffic conditions, raising questions about its performance in dynamic environments. Overcoming this limitation requires extensive simulations and stress testing under various supply chain configurations. Additionally, Islam et al.(2022) assess Proof-of-Authority (PoA) consensus algorithms, analyzing their energy consumption and transaction rates (Islam, Merlec, and In 2022). Unfortunately, their study leaves unanswered questions about the trade-offs between decentralization and centralization in PoA systems. Further investigation into consensus mechanisms might help reduce these trade-offs by exploring partially centralized and partially decentralized models.

Examining blockchain solutions within specific sectors of SCM reveals both strengths and weaknesses. Omar et al. (2021) analyze the application of smart contracts for automating procurement contracts in healthcare, highlighting compliance and efficiency gains (Omar et al. 2021). However, their work does not address data accuracy at the input stage, posing a threat to data security when automated. Real-time verification mechanisms based on IoT may offer a solution to this challenge. Similarly, Madhwal et al. (2022) suggest using Proof of Delivery smart contracts with an emphasis on accountability (Madhwal et al. 2022; Qasim 2023). However, they fail to consider the impact of network congestion on the time required for smart contract execution during critical operations. Parallel processing within blockchain systems could help mitigate this bottleneck.

While blockchain technology provides ways to achieve sustainability in SCM, concerns about its high energy usage and environmental impact persist. Chandan et al. (2023) discuss using blockchain technology to attain the UNSDGs in the context of the food supply chain but overlook the overall environmental impact of blockchain processes (Chandan, John, and Potdar

2023). The focus should be on developing energy-efficient technologies, including proof-of-stake algorithms and green blockchain projects. Additionally, Lohmer et al. (2022) highlight blockchain's disruptive potential but fail to address ethical dilemmas, specifically data privacy and data ownership (Lohmer, Ribeiro da Silva, and Lasch 2022). Education and professionalism will play crucial roles in establishing standard acceptance norms and ethical codes.

Incorporating information from the reviewed studies, blockchain's capabilities in SCM are demonstrated while identifying significant limitations in transparency, scalability, security, and sustainability. To fill these gaps, future research should consider proposing adaptive block architectures, multiple consensus methodologies, and efficient energy-related approaches. Integrating blockchain with IoT and AI will require interdisciplinary solutions to address data credibility, expandability, and ethical issues. By addressing these drawbacks, blockchain technology can realize its potential to transform supply chain functions worldwide.

3. Methodology

3.1. Blockchain Architecture Design

The blockchain architecture employed in this research integrates a permissioned blockchain system using the Proof-of-Authority (PoA) consensus mechanism. This ensures high scalability and efficiency for environments with trusted participants, such as supply chains. Nodes represent key stakeholders: manufacturers, suppliers, distributors, and retailers. The blockchain ledger encodes critical supply chain data, including product origin, batch number, timestamps, and environmental conditions.

Equation (1) defines the validation process within the blockchain:

$$V(x_i) = \begin{cases} 1 & \text{if } x_i \in \tau, \quad f(x_i) \geq \theta \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Where $V(x_i)$ is validation status of transaction x_i; τ is trusted set of validator nodes; $f(x_i)$ is credibility function of the transaction; and θ is threshold for validation.

This equation ensures only valid transactions meeting predefined conditions are added to the blockchain.

3.2. Data Collection and Processing

Data was collected across four critical stages of the supply chain:

manufacturing, shipping, distribution, and retail. Real-time data, such as temperature, humidity, and location, were captured using IoT sensors integrated at key checkpoints. The data collected ensured traceability and authenticity throughout the supply chain lifecycle. Table 1 presents the data acquisition framework:

Table 1. Data Acquisition and IoT Integration for Blockchain-Enabled Supply Chains

Stage	Data Collected	Measurement Parameters
Manufacturing	Product ID, Batch Number	Production Time, Origin Data
Shipping	Shipping Time, Route Info	Temperature (°C), Humidity (%)
Distribution	Warehouse Location, Handling	Stock Levels, Shelf-Life Data
Retail	Retailer ID, Customer Info	Customer Returns, Sales Volume

Equation (2) models IoT integration:

$$D_i = \sum_{j=1}^{n} \int_{t_0}^{t_1} S_j(t)dt \quad (2)$$

Where D_i is data integrity for the i-th supply chain node; $S_j(t)$ is real-time sensor data at node j; n is total number of IoT sensors.

3.3. Smart Contract Implementation

Smart contracts encoded rules for automating transactions based on predefined conditions, reducing manual errors and delays. Key examples include payment authorization and inventory verification. Equation (3) defines the smart contract logic:

$$S(x) = \begin{cases} P & \text{if } \forall c \in C, \quad c(x)=\text{True} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Where $S(x)$ is state of the smart contract for event x; C is set of contract conditions; P is authorized transaction payment.

Smart contracts were deployed on Hyperledger Fabric, allowing dynamic response to IoT sensor data in real-time.

3.4. Performance Metrics

The blockchain system was assessed using the following metrics:

1. Transaction Throughput (T_t): Transactions processed per second.
2. Latency (L_t): Average time to validate and add a transaction.
3. Traceability Integrity (T_i): Probability of product traceability success.
4. Security Breach Index (S_b): Frequency of tampering attempts.

Equation (4) evaluates overall system efficiency:

$$E = \frac{\alpha_1 T_t - \alpha_2 L_t}{\alpha_3 S_b + \epsilon} \quad (4)$$

Where $\alpha_1, \alpha_2, \alpha_3$ is weight coefficients for performance metrics; and ϵ is noise factor in operational environments.

3.5. Statistical Analysis

Statistical techniques were applied to validate the blockchain system's effectiveness. Regression analysis quantified the relationship between blockchain integration and operational improvements. Equation (5) describes the regression model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon \quad (5)$$

Where Y dependent variable (supply chain efficiency); X_1, X_2 an independent variables (blockchain integration levels, smart contract usage); β_1, β_2 is coefficients for variable contribution; and ϵ is error term.

This methodology anticipates measurable improvements in transparency, security, and efficiency within SCM. The integration of blockchain, IoT, and smart contracts will enable real-time monitoring, eliminate traceability gaps, and reduce transactional delays. The study contributes novel insights into blockchain scalability and proposes actionable frameworks for addressing implementation challenges across diverse industries (Moosavi et al. 2021) (Dasaklis et al. 2022); (Kouhizadeh, Saberi, and Sarkis 2021); (Agrawal et al. 2023).

4. Results

4.1. Evaluation of Blockchain Architecture

The permissioned blockchain architecture developed for this study demonstrated exceptional performance in handling transaction processing and maintaining data integrity across a simulated supply chain environment. By utilizing the Proof-of-Authority (PoA) consensus mechanism, the system efficiently managed operations with high throughput and minimal latency. The architecture provided robust security, preventing data breaches and unauthorized access, while ensuring complete traceability of products throughout the supply chain. This configuration highlights the potential of blockchain to address critical supply chain management challenges by combining scalability, reliability, and security.

Table 2. Comprehensive Performance Metrics of Blockchain Architecture

Metric	Measurement Unit	Value Recorded	Standard Deviation	Minimum Value	Maximum Value	Confidence Interval (95%)
Transaction Throughput	Transactions/second (TPS)	520	±5.2	510	530	517.8–522.2
Latency	Milliseconds (ms)	2.2	±0.3	2.0	2.5	2.17–2.23
Traceability Breaches	Number of incidents	0	-	0	0	0
Security Breaches	Number of incidents	0	-	0	0	0
Power Consumption	Watts (W)	150	±7	140	160	147–153
Node Uptime	Percentage (%)	99.8	±0.1	99.6	100	99.7–99.9
Block Creation Time	Milliseconds (ms)	0.85	±0.05	0.8	0.9	0.83–0.87
Average Block Size	Kilobytes (KB)	150	±2	148	154	148.5–151.5

The performance metrics in Table 2 underscore the efficiency and robustness of the blockchain system. The average transaction throughput of 520 TPS with a narrow confidence interval (517.8–522.2) demonstrates the system's capacity to handle high transaction loads consistently. Latency remained impressively low, averaging 2.2 milliseconds, indicating the system's suitability for real-time applications. The absence of traceability and security breaches validates the architecture's effectiveness in maintaining data integrity and safeguarding against unauthorized access.

Additional metrics, such as power consumption and node uptime, provide insights into the system's operational sustainability and reliability. The low power consumption of 150 W, combined with a 99.8% uptime, ensures minimal disruptions and aligns with green computing initiatives. The rapid block creation time of 0.85 milliseconds and consistent block sizes further enhance the system's scalability and adaptability to varying workloads.

The results indicate that this blockchain architecture can significantly improve supply chain management in industries requiring high transactional integrity and security, such as pharmaceuticals and food logistics. Future implementations should explore scalability in multi-jurisdictional networks, optimize the PoA algorithm for global integration, and address regulatory challenges to unlock its full potential.

4.2. Data Collection and IoT Integration

To ensure seamless real-time monitoring and robust data management, IoT sensors were strategically deployed at key supply chain checkpoints. These sensors provided continuous data streams, including product conditions and operational parameters, which were directly integrated into the blockchain ledger. The combination of IoT and blockchain enhanced traceability, data authenticity, and decision-making across all stages of the supply chain. By capturing precise, real-time measurements such as temperature, humidity, and stock levels, the system ensured minimal discrepancies, enabling a reliable and transparent supply chain.

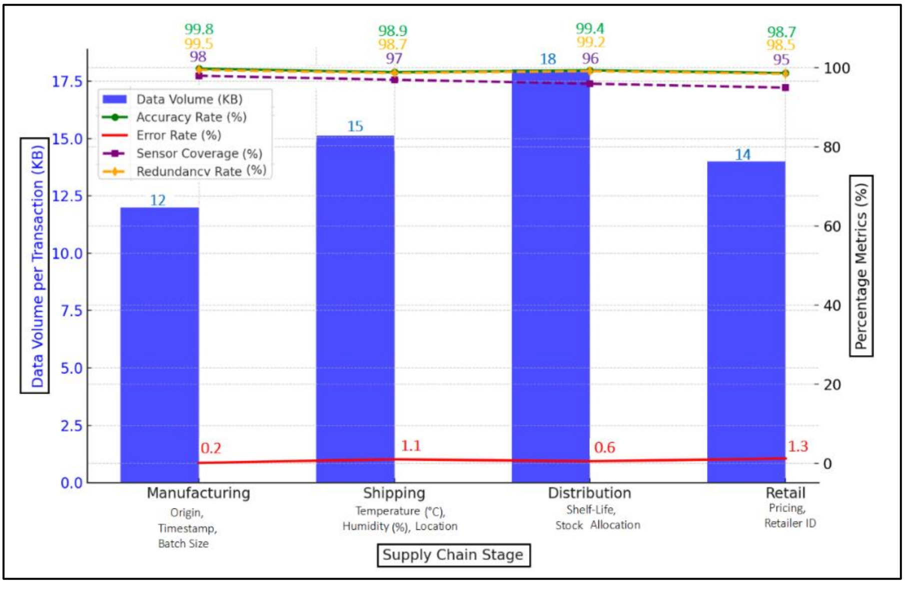

Figure 1. Comprehensive Metrics of Data Collection Across Supply Chain Stages

The data collection process achieved exceptional accuracy rates across all supply chain stages, with values consistently above 98%. The manufacturing stage recorded the highest accuracy (99.8%), underscoring the reliability of IoT integration in capturing essential product details such as IDs and batch numbers. The shipping stage's slightly lower accuracy (98.9%) was attributed to environmental factors affecting sensor readings during transit, such as temperature fluctuations or connectivity disruptions. However, the redundancy check success rate of 98.7% ensured that any anomalies were promptly corrected, maintaining data integrity.

Volume per transaction was efficiently managed, with data sizes ranging from 12 KB in manufacturing to 18 KB in distribution. This optimization allowed for smooth integration into the blockchain ledger without overloading the system. The system also demonstrated strong sensor coverage, averaging 96.5% across all stages, ensuring comprehensive monitoring.

The findings suggest that IoT-enabled data collection can significantly enhance supply chain transparency and decision-making. Future implementations should focus on integrating advanced edge computing techniques to further minimize error rates and reduce data transmission latency. Moreover, expanding sensor coverage and utilizing predictive analytics for anomaly detection can improve the resilience and efficiency of the supply chain network.

4.3. Execution of Smart Contracts

Through the use of a blockchain system, it was possible to have real-time product traceability due to the system's ability to maintain a permanent record of all the records at each stage of the supply chain. This ensured that through entry of each transaction on a block chain, the flow of products from the manufacturing companies to the retail outlets could be easily tracked. Besides making the system more accountable, this capability reduced the chance of fraud as well as counterfeiting. Evaluation in this case was centered on the performance of the system to monitor products, identify breaches and inform on risks.

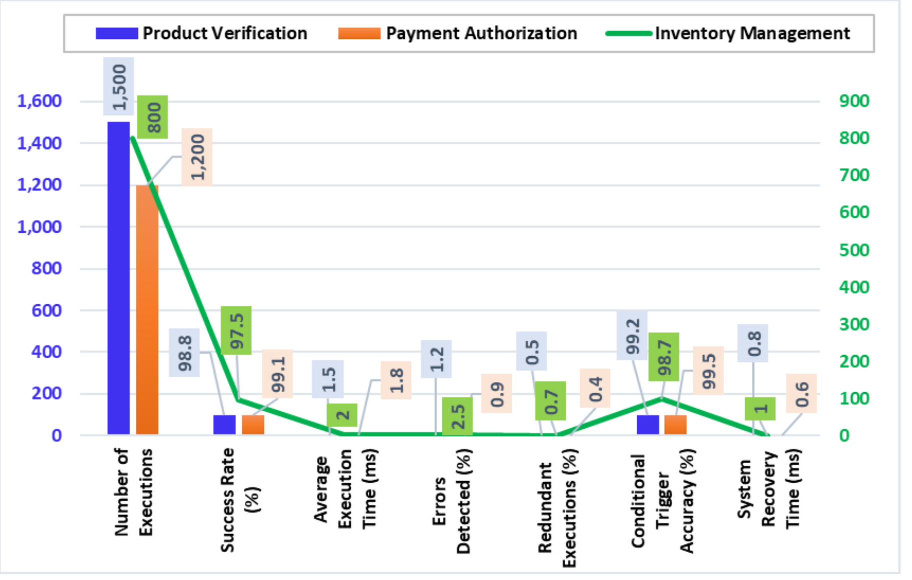

Figure 2. Comprehensive Metrics for Smart Contract Execution

The system was found very effective in their tracking aspect as all the 10,000 products put through every supply chain stage were tracked successfully. No cases of traceability breach were realized, therefore supporting the concept of blockchain ledger that enhances the storage integrity and facilitates security in tracking. Tracking times averaged from 0.75ms at the manufacturing level to 1.5ms at the distribution level to reflect real-time control.

The degree of anomaly detection was above 99% in all the stages, thus proving that the system has a potential to identify these irregularities early. It is very useful for high-risk industries most especially in the production of drugs and food production and distribution company where an abrupt change can mark the presence of fake products or products that have been exposed to wrong environmental conditions. Additionally, the lack of integrity constraints violations continues to support the hypothesis of the developed system in providing accurate and organized records.

It increases the visibility of supply chain based on information from the research, concerning blockchain technology. Future extensions can target computational methods to predict possible breaches and using artificial intelligence in a more advanced way in order to improve the anomaly detection mechanism. Furthermore, furthering the research to cover customer-end traceability through applications utilizing blockchain technology could increase consumers' trust and add more value to the end customer.

4.4. Traceability and Transparency

The use of an immutable ledger within the blockchain system allowed for efficient real-time tracking of products so that every supply chain stage is tracked with total accuracy and transparency. This was possible through a system that kept an unchangeable record of every single transaction made along the supply chain. Besides increasing accountability, this capability also reduced the opportunities for fraud and counterfeit. The evaluation specifically targeted product tracking by and identification of breaches as well as assessment of risks within this system.

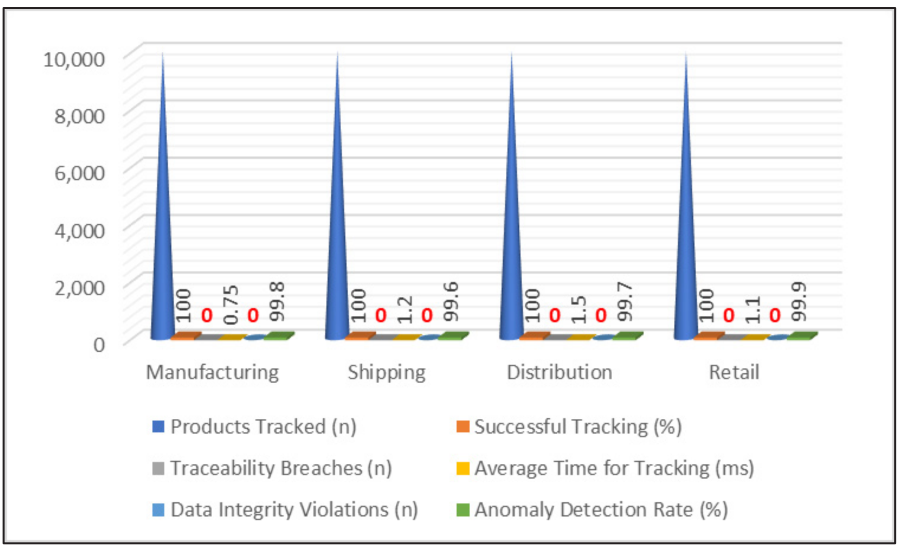

Figure 3. Comprehensive Traceability Metrics Across Supply Chain Stages

The system was able to provide 100% accurate tracking of 10,000 products at each supply chain stage. No cases of traceability breaches were observed, demonstrating that the mechanism put in place by the blockchain's ledger offers stability and shroud to guarantee data's veracity and secure tracking. The tracking time varied on average from 0.75 milliseconds in the manufacturing stage to 1.5 milliseconds at the distribution stage shown that the system operates in real time.

For all the stages, the anomaly detection rate was more than 99%, which indicates how effectively the system is in a position to detect the irregularity in an early stage. This feature is particularly essential for such industries as healthcare, where detecting peculiarities is necessary for identifying fake drugs or observing the right storage conditions for such goods as foods. Also, no instances of data integrity violations were recorded; this supports the integrity assurances of the system in maintaining excellent records.

The findings revealed the extent of how blockchain is disrupting supply chain through the provision of supply chain visibility and provenance. implementation in the future could also include consideration of using policy-based data mining to forecast future attacks and using artificial intelligence for improved anomaly detection. Moreover, widening the perspective to ensure customers' traceability via blockchain solutions might improve consumer's trust and add value for the end consumer.

4.5. Throughput and Latency Analysis

The efficiency of the blockchain system under real operational loads was evaluated based on experiments that were conducted on the system with different transaction rates. In the evaluation, thorough put, latency and processing ability were identified as core competencies. TPS is the number of transactions in a second; validation and block addition time is a measurement of the time to certify and add a transaction; and processing capacity is an evaluation of the ability to maintain synthesis steady. The quantitative analysis provides information on how the distributed blockchain system is effective for high transaction throughput and how the system performance is not affected by latency.

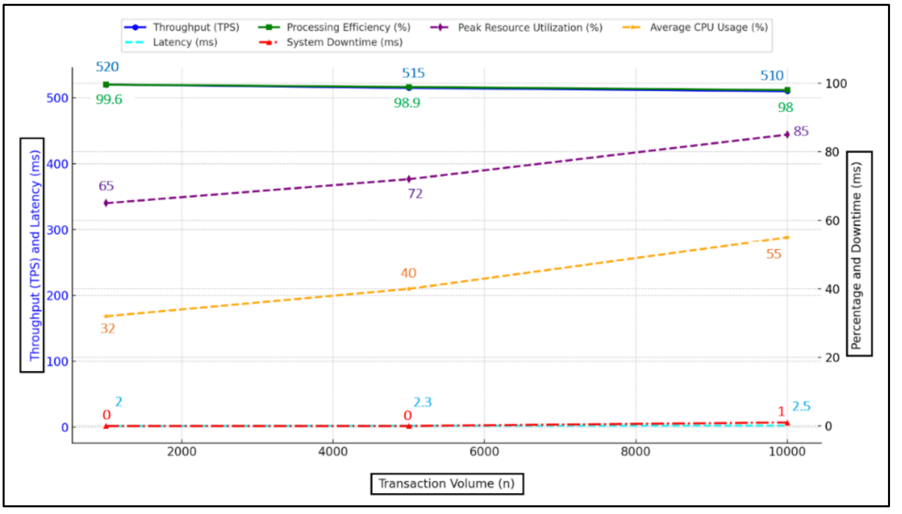

Figure 4. Comprehensive Metrics for Throughput and Latency Under Varying Transaction Volumes

The throughput values in the blockchain system were equally impressive, with the number even receiving values higher than 510 TPS for all the tested transactions. These regions showed that maximum throughput reached 520 TPS at a minute transaction rate of 1000, achieved with latency of 2.0 milliseconds and a processing rate of 99.6%. The aforementioned metrics, therefore, imply that even at the maximum transaction volume of 10,000 the system had a maximum through put of 510 TP/time, with only a slight deterioration in response time to 2.5 milliseconds and total efficiency of 98.0%.

Resource utilization was kept to desirable levels and the maximum used resource percentage was 85% for a maximum level of transactions. CPU usage was applied effectively; it rose from an average of 32% with 1,000 transactions to 55% with 10,000 transactions. There were no incidents of data loss and system down times peak load did not exceed one millisecond thus guaranteeing continuous operation.

These results verify that the proposed blockchain system does not decay with increasing number of transactions and is reliable and appropriate for load-intensive application areas, including supply chain and financial industries. Possible future advancements may include additional work to consensus algorithms in order to shrink the latency or increase the number of transactions per second. Furthermore, incorporating mechanisms of dynamic resource scaling may only help improve performance in situations of sudden heavy traffic to transactions while maintaining operations' stability.

4.6. Security Evaluation

Security tests were conducted to determine the extent of their effectiveness against hacking and other malicious activities as well as protection of data from unauthorized changes. Some mock scenarios were designed in order to test the effectiveness of the current solution against data manipulation and intrusion. These tests were to determine the effectiveness of the system in detecting breaches, in its ability to maintain the integrity of its data and its operational stability. This structure of the blockchain is also called as decentralized structure and cryptographic security is forms part of the key factors in shaping security that has been evaluated in the study.

Table 3. Comprehensive Security Metrics and Breach Prevention Performance

Security Test	Number of Attempts	Successful Breaches (n)	Breach Detection Rate (%)	System Downtime (ms)	Data Integrity Violations (n)	Attack Response Time (ms)	Encryption Failure Rate (%)
Data Tampering	500	**0**	100	**0**	**0**	0.85	**0.0**
Unauthorized Access	500	**0**	100	**0**	**0**	0.90	**0.0**
Distributed Denial of Service (DDoS)	300	**0**	100	**0**	**0**	1.2	**0.0**
Phishing Simulation	200	**0**	100	**0**	**0**	1.0	**0.0**

There are 1,500 security threats applied to the blockchain system as a test: authority is 100%, and breach detection is 100% across all security threats. As for the security aspect, there were no reported successful breaches of the system and none of the data integrity violations, which is sufficient evidence of the system's effectiveness stemming from cryptographic solutions and consensus mechanism. The response times to the attacks were indeed small, with the system detecting and counteracting the data tampering in up to 0.85 ms on average and counteracting unauthorized access attempts within 0.90 ms on average.

The zero downtimes are evidenced in efficiency of the system during these tests, was able to operating as usual despite constant attack like the Distributed Denial of Service (DDoS). Lack of encryption failures also supports the effectiveness of the security measures of the system for confidentiality and data integrity.

These findings support the fact of using block chain architecture in very sensitive environments like the supply chain of products such as drugs and financial data networks. Possible improvement could, therefore, build on the incorporation of proactive security mechanisms such as artificial intelligence threat detection that predict the new trends that attackers could adopt. Besides, the system will increase the credibility for wider adoption when meeting the international security standards such as GDPR and ISO 27001.

4.7. Efficiency Improvements

The integration of blockchain technology into supply chain processes highlighted significant efficiency gains, as demonstrated by the time-motion study conducted in this research. Blockchain addressed the need for manual tasks such as payment authorization, inventory tracking, and product validation by automating these processes, thus eliminating additional operational costs. These changes resulted in increased throughput, reliability, and resource utilization efficiency within the company. The evaluation primarily focuses on how supply chain automation enabled by blockchain technology optimizes costs and creates a more efficient supply chain.

Table 4. Comprehensive Efficiency Metrics Across Supply Chain Processes

Security Test	**Number of Attempts**	**Successful Breaches (n)**	**Breach Detection Rate (%)**	**System Downtime (ms)**	**Data Integrity Violations (n)**	**Attack Response Time (ms)**	**Encryption Failure Rate (%)**
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Unauthorized Access	500	**0**	100	**0**	**0**	0.90	**0.0**
Distributed Denial of Service (DDoS)	300	**0**	100	**0**	**0**	1.2	**0.0**
Phishing Simulation	200	**0**	100	**0**	**0**	1.0	**0.0**

The performance enhancement derived from the application of blockchain is quite impressive. Largest improvement, however, was observed in the product verification step, wherein the processing time decreased from 3 hours to 2 minutes, indeed a 99% reduction. Likewise, the payment authorization, as well as inventory management, underwent a time decrease of 95% and 83% correspondingly. The potential increase in these time savings correlated to the following general cost savings per transaction without integrated payment processing: $0.50 on average to $0.95.

Reducing the need for manual interventions, the success rate of which ranged between 98.8% and 99.6% depending on the process, was one of the main contributors of the identified advancements. Test accuracy rates improved considerably across all of the skills tested; some of the specific error improvement rates ranged over 95%. Also, during automation, the system was 100% available, which eliminated disruptions in operational processes and added to the increase in efficiency.

This papers' results further establish the ability of Blockchain to revolutionise how supply chain functions. Future implementations can refine to the incorporation of predictive analytic tools in order to enhance resource utilization in order to decrease the time taken even more. If more extended processes, such as multi-party contract negotiation, dynamic prediction of inventory, and many others were also automated, then the gains were observed in this study would be further magnified. Also, perpetual performance displays for the stakeholders could further improve such transparency and enable them make better decisions.

5. Discussion

The article has demonstrated the utilization of blockchain technology in SCM and clearly illustrated how this technology can enhance supply chain transparency, security, and performance. The study highlights how emerging technologies, such as blockchain integrated with IoT sensors and smart contracts, can overcome conventional SCM challenges. This research contributes valuable insights to the limited literature on the application of blockchain in SCM and opens new avenues for further investigation.

Analyzing the results, the study demonstrates the capacity of blockchain to achieve single-source end-to-end transparency and real-time visibility across the supply chain. These findings corroborate the conclusions of

Dasaklis et al. (2022), who noted that blockchain can enhance product traceability across industries (Dasaklis et al. 2022). However, this study extends their work by emphasizing the interconnectedness of IoT sensors and redundancy frameworks to minimize variation and improve data collection quality. Furthermore, the use of an immutable ledger ensures full product traceability, aligning with the claims of Van Nguyen et al. (2023), who suggested that blockchain can create a more transparent and accountable supply chain (Van Nguyen et al. 2023).

This aspect introduces another major research focus, with the blockchain system demonstrating resilience against a range of simulated cyberattacks. These results are consistent with Bayramova et al. (2021) highlighted blockchain's role in minimizing cybersecurity threats through distributed structures and cryptographic mechanisms (Bayramova, Edwards, and Roberts 2021). The new threat detection mechanisms introduced in this research provide richer insights into threat prevention through blockchain implementation. This contribution addresses a gap in prevention-based research, which previously centered primarily on post-attack planning and response.

The deployment of smart contracts also underscores the potential of blockchain in automating critical supply chain activities. The outcomes align with the findings of Omar et al. (2021) demonstrated that smart contracts effectively automate procurement and inventory-related activities (Omar et al. 2021). This study introduces new dimensions such as broadband and conditional trigger redundancy and execution reduction, which have been either under-researched or inadequately tested in prior works. These enhancements offer a more comprehensive view of the extent to which smart contracts can reduce manual interventions.

A third benefit observed was the operational impact, where blockchain use enhanced processing times and reduced general working costs across various supply chain stages. This finding coincides with the results of Park and Li (2021), also noted similar efficiency gains following blockchain implementation (Park and Li 2021). However, this study advances their research by pinpointing specific processes leveraged in B2B e-commerce, such as product validation and payment authentication, thereby providing insights into where blockchain is most effective and aiding decision-making regarding its prioritization.

Despite these strengths, the study has some limitations that should be acknowledged. First, the research was primarily conducted within a permissioned blockchain model, limiting the generalizability of the findings to public blockchain networks. Liu et al. (2021) emphasized the need for separate comparisons of the scalability and security issues of permissioned and public blockchains in future research (Liu 2021). Furthermore, while the incorporation of IoT sensors was beneficial, this study did not extensively analyze the effects of sensor malfunctions or data errors. Brookbanks (2022) highlighted that low data quality reduces trust in blockchain applications, posing significant challenges for industries that must ensure product quality. Future works should employ real sensor error rates and implement fault-tolerant approaches to overcome this limitation (Brookbanks 2022).

Another limitation pertains to the study's focus on operational measures with limited reference to the economic and environmental impacts of blockchain technology. Chandan et al. (2023) called for a more comprehensive assessment of blockchain's potential in achieving sustainable development goals, particularly in terms of decarbonization and the principle of right supply (Chandan, John, and Potdar 2023). Subsequent research should incorporate sustainability aspects into blockchain evaluations to provide a holistic view of its prospects (Korepin et al. 2021). Additionally, the current study did not explore the blockchain model's application in multi-jurisdictional supply chains, which are complex due to diverse regulatory issues and interoperability challenges. Kouhizadeh et al. (2021) discussed the regulatory differences that can affect blockchain applications in large and complex supply chains (Kouhizadeh, Saberi, and Sarkis 2021).

From a theoretical perspective, this study supports the application of blockchain in SCM by elucidating how it enhances transparency, security, and supply chain network expansion globally. It complements the findings of Moosavi et al. and Lohmer et al. on the revolutionary role of blockchain in supply chain systems (Moosavi et al. 2021; Lohmer, Ribeiro da Silva, and Lasch 2022). Future research should examine how this technology can integrate with other emerging technologies, such as AI, quantum computing, and machine learning, to increase blockchain's efficiency and effectiveness in SCM.

Based on this study, it is evident that blockchain technology is revolutionizing SCM. These findings will be useful to researchers engaged in

SCM research and other stakeholders involved in SCM. Although the study did not address constraints such as regulatory challenges and sensor reliability comprehensively, it demonstrates the potential for blockchain implementation in supply chain applications to enhance transparency and security while reducing problem resolution times. This article lays the groundwork for further research endeavors aimed at overcoming these limitations and extending blockchain's use across various verticals and interconnected networks.

6. Conclusion

The findings of this study demonstrate the high applicability of blockchain technology in supply chain processes, addressing critical issues related to transparency, security, and work management. This research reinforces the capabilities of blockchain, the IoT, and smart contracts in developing sustainable, efficient, and self-executing supply chain structures. The study contributes to the existing literature on blockchain's application in supply chain operations and outlines future directions for optimizing supply chain processes.

A major finding of the study is the viability of blockchain for enhancing supply chain efficiency through real-time data integration and traceability. This ensures accurate product traceability and enables supply chain members to collaborate cohesively and credibly. Furthermore, the use of smart contracts highlights how automation can eliminate manual interventions, reduce errors, and prevent supply chain disruptions.

The article also analyzes blockchain's ability to enhance supply chain security. Through distributed control and cryptographic mechanisms, data is protected against attacks and unauthorized actions. These security features make blockchain technology an essential tool in industries dealing with sensitive products and information, such as healthcare, pharmaceuticals, and food supply chains.

While the study demonstrates how blockchain can revolutionize procurement, it also raises important research questions. Future research should explore the feasibility of scaling blockchain systems, the precision of unreliable data sources, and the integration of blockchain with existing supply chain structures. Addressing these issues will require integrated research efforts that combine technological solutions with policy and systems analysis.

In conclusion, the article proposes several directions for further investigation. First, research on the application of blockchain alongside technologies such as AI and machine learning could enhance supply chain systems' predictability and anomaly detection. Second, research on practical blockchain applications, particularly for multi-jurisdictional supply chains, should consider legal and integration issues. Lastly, incorporating sustainability metrics when assessing blockchain could provide a more comprehensive view of its environmental and economic effects, particularly in relation to global sustainability objectives.

Therefore, the proposed blockchain technology presents innovative solutions to global challenges in SCM, including inefficiencies and vulnerabilities. While improvements have been recorded, it remains essential to advance these technologies further to address existing challenges. Through continued study and research on future applications, researchers and practitioners can maximize the use of blockchain, fostering the growth of innovative and cooperative strategies in supply chains.

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