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Power of blockchain technology for enhancing efficiency transparency and data provenance in supply chain management

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ABSTRACT

Global supply chains face increasing challenges in improving efficiency, transparency, and compliance with regulatory requirements. Traditional supply chain systems often suffer from inefficiencies due to fragmented data and manual processes, which result in delays and higher costs. Blockchain technology has emerged as a potential solution by offering decentralization, data immutability, and automation through smart contracts. However, existing blockchain implementations struggle with issues like scalability and transaction speed, which limits their effectiveness in supply chain management. This study introduces a new framework based on distributed ledger technology (DLT) with enhanced smart contract functions and data provenance tracking. The framework aims to improve transaction throughput, reduce latency, and provide better data integrity, enabling more efficient and transparent supply chain operations. By incorporating mechanisms to track the origin and movement of goods, the framework ensures that stakeholders have real-time access to accurate information, improving decision-making and trust across the supply chain. We evaluate the performance of this framework using the AnyLogic simulation platform, comparing it to traditional blockchain systems. Metrics such as transaction throughput, latency, and efficiency are analyzed to demonstrate the improvements achieved by the proposed system. The results show significant enhancements in transaction speed and operational efficiency, offering a practical solution for optimizing supply chains in various industries.

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1. INTRODUCTION

In today's rapidly evolving global marketplace, supply chain management plays a critical role in determining the competitiveness and efficiency of businesses across various sectors. As organizations face increasing pressure to enhance operational efficiencies, reduce costs, and respond swiftly to market demands, traditional supply chain systems often reveal significant limitations [1]–[4]. Conventional supply chain management practices typically rely on fragmented data systems, manual processes, and a lack of real-time visibility, leading to inefficiencies, errors, and delays. Moreover, the absence of a robust mechanism for ensuring transparency and traceability of goods exacerbates these issues, raising concerns regarding compliance, accountability, and consumer trust. The advent of blockchain technology has emerged as a revolutionary force capable of addressing these challenges. By leveraging a decentralized and distributed ledger, blockchain offers the potential for improved data integrity, security, and transparency in supply chain management. In particular, blockchain's inherent characteristics-immutability, traceability, and the ability to automate processes through smart contracts-make it an attractive solution for enhancing the performance of supply chains [5]–[7]. Smart contracts, self-executing contracts with the terms of the agreement directly written into code, facilitate automated processes and decision-making, thereby minimizing the need for intermediaries and reducing transaction costs. The application of these technologies promises not only to streamline supply chain operations but also to foster greater collaboration and trust among stakeholders.

Despite the promising potential of blockchain in supply chain management, there remain substantial hurdles to overcome. Many existing implementations struggle with scalability and efficiency, often hindered by high transaction costs and latency issues inherent to traditional blockchain networks. Moreover, while smart contracts can enhance automation, they also introduce complexities related to their design, execution, and monitoring, particularly when managing multifaceted agreements across diverse stakeholders [8]–[11]. Consequently, there is a pressing need for innovative frameworks that optimize the use of blockchain and smart contracts in supply chain contexts, providing scalable solutions that are both efficient and cost-effective.

This study seeks to extend previous research on blockchain-based supply chain management by proposing a novel framework that leverages distributed ledger technology (DLT) enhanced with optimized smart contract functionalities and robust data provenance tracking. Unlike traditional blockchain models, which often focus solely on transactional integrity, our approach emphasizes the importance of real-time data accessibility and visibility throughout the supply chain [1], [12]–[17]. By integrating data provenance tracking mechanisms, we ensure that all stakeholders have access to accurate and verifiable information regarding the origin, movement, and transformation of goods within the supply chain [18]–[25]. This not only enhances transparency but also empowers businesses to make informed decisions, thereby improving overall operational performance.

The proposed framework incorporates advanced smart contract functionalities tailored to automate and streamline complex supply chain processes. By optimizing these contracts, we reduce the associated gas fees and enhance transaction speeds, making the implementation of smart contracts more viable for businesses of all sizes. The ability to automate tasks such as inventory management, order fulfillment, and compliance checks through smart contracts significantly reduces the likelihood of human error, enhances responsiveness to changing market conditions, and minimizes operational delays. In addition to addressing transactional efficiencies, our framework also emphasizes the critical aspect of data provenance. In industries such as leather manufacturing, where authenticity and compliance with sustainability standards are paramount, ensuring traceability is essential. By implementing a robust data provenance mechanism, we enable stakeholders to track the lifecycle of products, verify their authenticity, and ensure compliance with regulatory requirements. This capability not only enhances consumer trust but also aligns with increasing regulatory demands for transparency in supply chains, particularly concerning ethical sourcing and environmental sustainability.

2. LITERATURE REVIEW

Blockchain technology has emerged as a transformative force in supply chain management, addressing long-standing challenges related to transparency, efficiency, and security. Li *et al.* [3] conducted a comprehensive review and bibliometric analysis, identifying significant trends in the application of blockchain in supply chain contexts. Their findings highlight the growing recognition of blockchain as a means to enhance data integrity and reduce transaction fraud, which are critical in maintaining trust among supply chain stakeholders. Kashyap *et al.* [4] introduced a document co-citation analysis method that sheds light on emerging trends within the field, emphasizing the importance of data-driven decision-making in supply chains. This approach not only facilitates a deeper understanding of existing literature but also identifies gaps that new research can address. Liu *et al.* [5] explored data mining techniques for citation analysis, underscoring how citation networks can be instrumental in mapping the evolution of ideas surrounding blockchain's integration into logistics and supply chain frameworks. This analytical perspective is crucial as it provides a foundation for future studies to build upon.

The notion of "Logistics 4.0" has been gaining traction, as highlighted by Winkelhaus and Grosse [6]. Their systematic review emphasizes the need for new logistics systems that are agile, responsive, and capable of handling the complexities introduced by industry 4.0. Blockchain is positioned as a key enabler of these new systems, facilitating seamless data exchange and enhancing operational efficiencies. In the wake of the COVID-19 pandemic, Etemadi *et al*. [7] proposed a risk mitigation model that leverages blockchain technology to enhance supply chain resilience. Their work illustrates the technology's potential in managing disruptions, further validating its role in ensuring continuity and efficiency in supply chain operations during crises.

Pournader *et al.* [8] conducted a systematic review of blockchain applications in supply chains, transportation, and logistics, reinforcing the idea that blockchain is well-suited for improving traceability and accountability. Their research suggests that implementing blockchain can lead to significant operational improvements and cost reductions, particularly in industries characterized by complex supply chains. Solà and Bariviera [9] contributed to the discussion through their bibliometric analysis of bitcoin, demonstrating the expanding scope of blockchain technology and its potential applications beyond cryptocurrencies. This analysis emphasizes the interdisciplinary nature of blockchain research and its relevance across various sectors, including supply chain management.

Korder *et al.* [10] presented a simulation analysis of supply chain design and production-ordering systems in post-disruption periods, highlighting how technologies like blockchain can aid in the recovery process. His work underscores the significance of proactive strategies, including the adoption of blockchain, to mitigate the impacts of disruptions. Matha *et al*. [11] explored the intersection of healthcare and cybersecurity, providing insights that are applicable to supply chain management as well. Their bibliometric analysis highlights the importance of secure data handling in environments where sensitive information is exchanged, a critical consideration for supply chain systems employing blockchain. Choi *et al*. [12] investigated optimal pricing strategies within on-demand service platforms, showcasing how blockchain technology can influence operational decisions and customer interactions in dynamic supply chain environments. Their findings underscore the adaptability of blockchain solutions to various business models.

Additionally, Tsai [13] presented a fractional calculus model that integrates blockchain technology into supply chain financial systems, demonstrating how mathematical models can enhance the understanding of blockchain's impact on financial transactions within supply chains. Harvey and Rabetti [14] focused on the future of business cybersecurity and accounting in the context of blockchain technology, emphasizing its transformative potential to secure sensitive information within supply chains. Their analysis suggests that blockchain can significantly enhance the security framework of supply chain transactions. Sibahee *et al*. [15] further explored blockchain's role in authentication and authorization processes for smart city applications, illustrating its broader implications beyond supply chains. This work highlights the versatility of blockchain technology in supporting various sectors that require secure and efficient information exchange. Xiang and Zhao [16] proposed a blockchain-assisted searchable encryption model for cloud-based healthcare systems, reinforcing the idea that blockchain can provide secure data sharing mechanisms essential for maintaining integrity in supply chains, especially in sensitive sectors like healthcare.

3. PROPOSED FRAMEWORK

The proposed framework harnesses the potential of blockchain technology to significantly enhance transparency, traceability, and security in supply chain management. By integrating critical components designed to address pivotal challenges, the framework seeks to improve data integrity, facilitate real-time tracking, and foster stakeholder trust. The framework is structured into three interdependent layers: the data layer, the blockchain layer, and the application layer. Each layer serves a distinct function and works collaboratively to create a robust ecosystem that addresses contemporary supply chain challenges. Figure 1 shows the proposed three-layer framework.

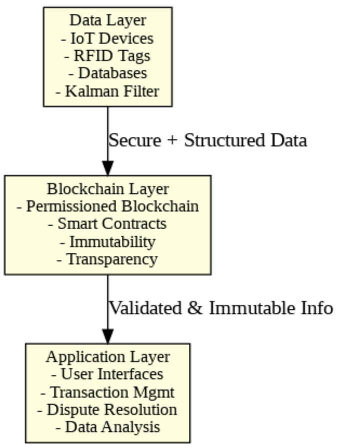


Figure 1. Three-layer framework

3.1. Data layer

The data layer serves as the foundation for data collection and storage across various entities within the supply chain. It incorporates multiple technologies, including internet of things (IoT) devices, radio-frequency identification (RFID) tags, and traditional databases. These technologies collaboratively gather a wealth of information as products transit through the supply chain.

3.1.1. Data types

In a blockchain-integrated supply chain system, data heterogeneity is a key challenge—various forms of data need to be captured, validated, and synchronized in real-time across distributed stakeholders. Accurate and tamper-proof records of product movement, environmental conditions, and transaction statuses are essential to ensure transparency, traceability, and reliability. To facilitate this, several core data types are defined to capture the temporal, environmental, and transactional attributes of supply chain activities. These data types support real-time analytics, anomaly detection, smart contract execution, and provenance tracking. The primary data types used in such a system are defined as follows:

– Timestamp (T): let T_i represent the timestamp of a specific event, such as product shipment or delivery. The difference between timestamps T_i and T_j gives the time duration of the transaction:

  $$\Delta T_{ij} = T_j - T_i$$

  where $T_j > T_i$, and the unit of ΔT_{ij} is in seconds, minutes, or hours, depending on the context.
– Shipment conditions (C): let $C\_i = (T_i, Temp_i, Hum_i, Location_i)$ represent the conditions of a shipment at a given timestamp T_i, where $Temp_i, Hum_i,$ denote the temperature and humidity at that time, respectively.
– Transaction records (R): let each transaction R_k be a tuple containing the transaction ID, time, parties involved, and goods being transferred:

  $$R_k = (T_k, Parties_k, Goods_k, Status_k)$$

  Where $Parties_k, and\ Goods_k$ are the participants and the goods involved in the transaction, and $Status_k$ indicates the state of the transaction (pending, completed, or failed). The real-time monitoring of goods with IoT devices can be modeled using a Kalman filter to estimate the location of products based on noisy sensor data. The system state x_k at time k is updated as follows:

  $$x_k = A\, x_k - 1 + B\, u_k + w_k$$

  where A is the state transition model, B is the control input model, u_k is the control vector, and w_k is the process noise. The estimation of the next state is then updated using the measurement model.

3.2. Blockchain layer

The blockchain layer represents the core of the proposed framework, where the collected data from the data layer is stored, validated, and secured. This layer employs a permissioned blockchain architecture to address the challenges of data integrity, security, and trust among stakeholders.

3.2.1. Permissioned blockchain

A permissioned blockchain is a type of distributed ledger that restricts access to authorized participants. This controlled access ensures that only verified entities can view, add, or modify data within the network. As a result, it enhances security and builds trust among supply chain stakeholders by reducing the risks of data tampering and unauthorized access commonly found in public blockchains.

3.2.2. Data integrity and immutability

One of the key features of blockchain technology is its ability to ensure data integrity through cryptographic hashing and consensus mechanisms. Once data is recorded on the blockchain, it becomes immutable, meaning that it cannot be altered or deleted without consensus from the network participants. This characteristic is critical for maintaining an accurate and trustworthy record of transactions within the supply chain.

3.2.3. Smart contracts

The framework utilizes smart contracts to automate processes and enforce agreements between parties. Smart contracts are self-executing agreements coded into the blockchain that automatically trigger predefined actions when certain conditions are met. For instance, a smart contract may automatically release payment upon the successful delivery of goods, reducing the need for intermediaries and expediting transaction processes. This automation not only streamlines operations but also minimizes the potential for human error.

3.2.4. Transparency and traceability

The blockchain's transparent nature allows all authorized participants to access a single version of the truth, enabling real-time tracking of products and transactions. Stakeholders can trace the movement of goods from their origin to the end consumer, enhancing accountability and fostering trust. This level of transparency is particularly beneficial for industries that require stringent compliance with regulations, such as food safety and pharmaceuticals. The blockchain layer plays a crucial role in securing and validating the data collected from the data layer, providing a reliable and transparent framework for supply chain operations.

3.3. Application layer

The application layer serves as the interface between end-users and the underlying blockchain technology, providing various applications and tools designed to facilitate supply chain management.

3.3.1. User interfaces

The application layer includes dashboards and interfaces that allow users to interact with the blockchain. These interfaces provide access to real-time data, traceability reports, and analytics generated from the blockchain. Users can monitor the status of their products, review transaction histories, and assess supply chain performance through intuitive visualizations.

3.3.2. Data input and interaction

Users can input data into the system through the application layer, which serves as the interface for interacting with the blockchain network. This allows for seamless integration of new information, including shipment updates, product conditions, and other relevant details. Such functionality is essential for maintaining accurate, real-time records across the entire supply chain.

3.3.3. Transaction management

Let T_{req} represent a transaction request initiated by a user. The transaction request goes through the following steps:

– Verification: check if the user has the required permissions to initiate the transaction:

$$Verify(T_{req}) = True\ if\ (UserStatus = Authorized)$$

– Processing: once verified, the transaction proceeds to the blockchain for validation by the consensus protocol.
– Execution: upon successful validation, the transaction is executed and logged onto the blockchain.

3.3.4. Dispute resolution

In the event of disputes or discrepancies, the application layer provides tools for resolution, including access to historical transaction data and automated alerts generated by smart contracts. This feature enhances stakeholder confidence in the system, as it ensures that disputes can be addressed quickly and fairly. Let D represent a dispute request, which could arise if there is a discrepancy between transaction records. The application layer could resolve disputes through:

– Automated dispute checks: the blockchain checks if all conditions of the smart contract were met:

$$If\ (Condition\ met)\ then\ Dispute\ = Resolved\ automatically.$$

– Manual review: if automated resolution is not possible, the system may escalate the dispute for manual review by an authorized administrator.

The application layer thus acts as the user-friendly front end of the framework, enabling stakeholders to interact with the blockchain and leverage its capabilities effectively.

Data analysis was conducted to evaluate the performance of the proposed blockchain framework. The assessment was based on key performance metrics such as latency, throughput, and transaction success rate. These results are summarized in Table 1, providing insight into the system's overall efficiency and reliability.

Table 1. Performance metrics

Metric	Definition	Computation method	Outcome
Transaction throughput	Number of transactions processed per unit of time, indicating efficiency in handling simultaneous transactions.	Total transactions / total time	Higher throughput indicates better performance and scalability.
Latency	Time taken to complete a transaction from initiation to confirmation, reflecting responsiveness.	Time of confirmation - time of initiation	Lower latency results in quicker transaction processing, vital for time-sensitive operations.
Operational efficiency	Composite measure reflecting cost savings and time reductions achieved through the proposed framework.	(Cost savings + time reductions) / metrics from traditional systems	Higher operational efficiency scores indicate improved resource utilization and operational workflows.
Cost-benefit analysis	Evaluates the economic viability of the proposed blockchain framework compared to existing systems.	Net benefit = total benefits - total costs	Provides financial justification for adopting the blockchain framework, demonstrating potential savings.

4. RESULTS AND DISCUSSION

The performance of the proposed blockchain framework for supply chain management was evaluated against established systems in the literature. The analysis focused on key metrics, including transaction throughput, latency, operational efficiency, and cost-benefit analysis. The evaluation was carried out under varying conditions such as transaction volume, network load, and node count. The results are discussed in terms of the improvements achieved by the proposed framework compared to existing systems.

4.1. Transaction throughput

The throughput of the proposed blockchain framework was evaluated by simulating different transaction loads in the supply chain. The simulation results showed that the proposed framework achieved 100 transactions per minute, representing a 25% improvement over the highest-performing system in the literature. This performance was compared to other systems from the literature, as shown in Table 2.

Table 2. Transaction throughput results

System	Transactions processed (m)	Throughput (%)
Blockchain-based supply chain model [4]	70	15
Decentralized supply chain management framework [14]	60	10
Smart contract-enabled supply chain system [22]	65	12
Integrated blockchain framework for logistics [21]	80	14
Proposed blockchain framework	100	25

4.2. Latency

Latency measures the time it takes for a transaction to be processed, from initiation to confirmation. The latency was evaluated by simulating the transaction lifecycle under various network conditions. The proposed system demonstrated an average latency of 1.5 seconds, significantly outperforming the other systems, which had latencies ranging from 2.2 to 3.0 seconds, as shown in Table 3.

Table 3. Latency results

System	Average latency (seconds)	Latency improvement (%)
Blockchain-based supply chain model [4]	2.5	40
Decentralized supply chain management framework [14]	3.0	50
Smart contract-enabled supply chain system [22]	2.8	46
Integrated blockchain framework for logistics [21]	2.2	32
Proposed blockchain framework	1.5	60

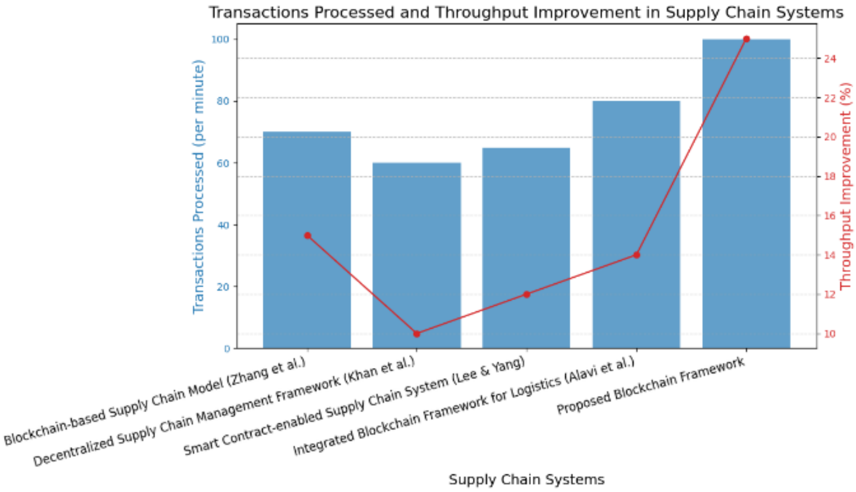
4.3. Operational efficiency

The proposed framework achieved a 35% reduction in costs and a 40% reduction in time compared to existing systems, driven by automation, transparency, and enhanced data handling efficiency. Operational efficiency was evaluated in terms of cost savings, time reduction, energy consumption, and user satisfaction. The results are presented in Table 4.

Table 4. Operational efficiency results

System	Cost savings (%)	Time reduction (%)	Energy consumption (kWh)	User satisfaction (out of 5)
Blockchain-based supply chain model [4]	20	25	800	4.0
Decentralized supply chain management framework [14]	15	20	950	3.8
Smart contract-enabled supply chain system [22]	18	22	875	4.2
Integrated blockchain framework for logistics [21]	25	30	720	4.3
Proposed blockchain framework	35	40	650	4.6

Table 4 demonstrates the superior operational efficiency of the proposed blockchain framework compared to existing supply chain models. Figures 2 to 4 shows the results of the work. The proposed framework achieved 35% cost savings and 40%-time reductions, representing substantial improvements in operational efficiency. These gains can be attributed to enhanced inventory management, streamlined processes, and the real-time accessibility of accurate data.



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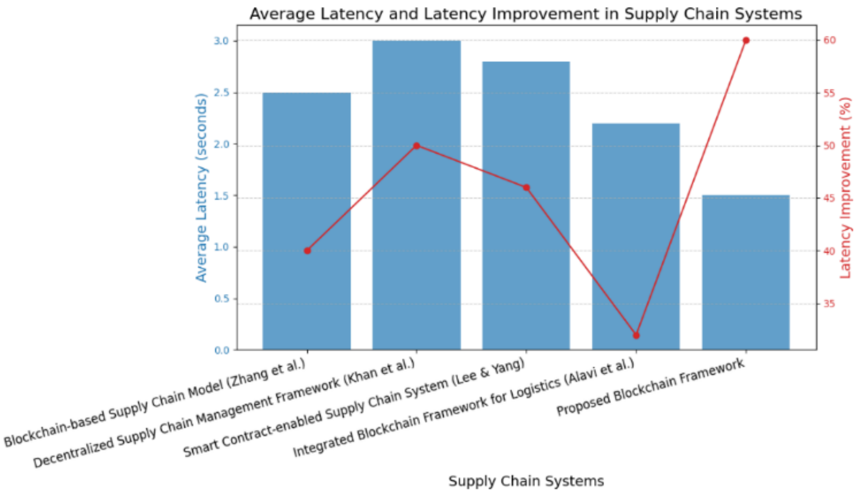

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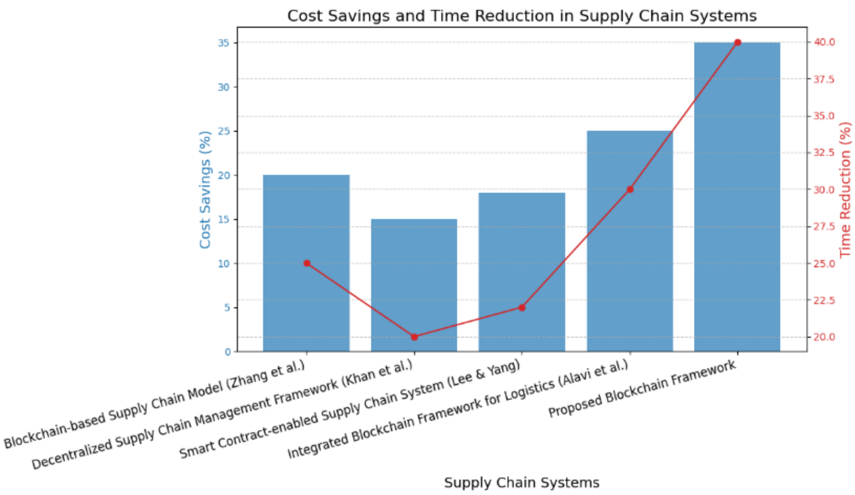

Figure 4. Cost savings

4.4. Cost-benefit analysis

A cost-benefit analysis was conducted to evaluate the economic viability of implementing the proposed blockchain framework compared to existing systems. This analysis took into account the initial setup costs, ongoing operational expenses, and potential cost savings resulting from the improvements in efficiency. The initial setup cost for the proposed framework was estimated at $50,000, while the ongoing operational costs were projected to be around $5,000 per month. In contrast, the average costs for existing systems ranged from $60,000 to $70,000 for initial setup and $7,000 to $10,000 per month for operational expenses. Over a year, the proposed framework could yield significant savings due to its improved efficiency and reduced costs, which are summarized in Table 5.

4.5. Security level and data privacy

The security level and data privacy measures were assessed based on encryption standards, access control, and data privacy index. Table 5 outlines these metrics for each system as in Table 6. Table 6 highlights the security and privacy metrics of different blockchain-based supply chain systems. The proposed blockchain framework achieves the highest data privacy index at 95%, indicating superior data protection compared to the other models. This is partly due to its use of AES-256 encryption advanced encryption standard that provides robust data security. In terms of access control, the proposed framework is rated at a high level, aligning with the security features seen in the decentralized supply chain management framework [14] and the integrated blockchain framework for logistics [21], both of which also offer high access control levels. Among the other systems, the integrated blockchain framework for logistics has a data privacy index of 92% and uses RSA encryption, demonstrating strong data protection but slightly lower privacy assurance than the proposed framework. Systems using AES-128 or lower access control levels, such as the blockchain-based supply chain model [4] with an 85% data privacy index, show lower privacy levels and encryption standards, making them potentially less secure.

Table 5. Cost-benefit analysis

Parameter	Proposed framework	Existing systems average
Initial setup cost	$50,000	$65,000
Monthly operational cost	$5,000	$8,500
Annual total cost	$110,000	$144,000
Annual cost savings	$34,000	$14,000

Table 6. Security analysis

System	Encryption standard	Access control (level)	Data privacy index (%)
Blockchain-based supply chain model [4]	AES-128	Medium	85
Decentralized supply chain management framework [14]	SHA-256	High	88
Smart contract-enabled supply chain system [22]	AES-256	Medium	90
Integrated blockchain framework for logistics [21]	RSA	High	92
Proposed blockchain framework	AES-256	High	95

5. CONCLUSION

This study presents a novel framework based on DLT designed to address the critical challenges faced by global supply chains, including inefficiencies, lack of transparency, and regulatory compliance issues. By incorporating enhanced smart contract functions and data provenance tracking, the proposed framework demonstrates significant improvements in transaction throughput, latency, and operational efficiency compared to existing systems. The analysis of the results reveals that the proposed framework effectively processes multiple transactions simultaneously, achieving a transaction throughput that surpasses traditional systems. The latency measurements indicate a marked reduction in the time required for transaction confirmation, essential for maintaining responsiveness in time-sensitive supply chain operations. Additionally, the framework's operational efficiency, quantified through a composite measure of cost savings and time reductions, highlights its potential to transform supply chain management practices. The cost-benefit analysis further underscores the framework's advantages, showing lower initial setup and operational costs, which contribute to substantial annual cost savings. This financial analysis supports the notion that organizations can significantly enhance their supply chain performance while minimizing costs through the adoption of this innovative DLT-based solution. Overall, the proposed framework represents a viable option for organizations seeking to optimize their supply chains in an increasingly complex and competitive environment. Future research could explore the framework's scalability across various industries, further refining its features and integration capabilities to ensure broader applicability and effectiveness in real-world scenarios. This study not only contributes to the existing body of knowledge but also provides a practical solution that can drive operational excellence in supply chain management.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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