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Addressing Supply Chain Inefficiencies in Nigeria Manufacturing: A Blockchain-Enabled Frameworks for Enhanced Visibility and Traceability

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Abstract

This paper assesses the performance implication of blockchain implementation in manufacturing supply chains in South-West Nigeria through a quasi-experimental, pre-post, and mixed-methods study. The data on the quantitative key performance indicator (KPI) of 150 manufacturing companies and the qualitative data of 100 top executives were examined. The results suggest that, the use of blockchain has a high level of traceability (up to 95%), reduced fraud (≈90%), and cost effectiveness (≈70%). Though, the results shows positive performance improvement, but the issues related to the initial investment, system interoperability, lack of scalability, and regulatory uncertainty still exist. The paper suggests a blockchain-based supply chain system that connects the technological elements and quantifiable performance indicators which can provide useful evidence-based advice to policy-makers and industry stakeholders.

1. Introduction

The Fourth Industrial Revolution has transformed the manufacturing process, and now it is easier to create smart factories due to the overall integration of the systems (Fatorachian and Kazemi, 2021). The application of blockchain technology in supply chains of manufacturing can bring expected benefits especially in spheres that need the transparency, the traceability and the efficiency. This study by Musa and Musa (2025) explores the impacts that blockchain technology is having on the supply chain systems particularly to the Nigerian market. These technological advances have to be supported by similar development of administrative systems to promote compliant and lawful operations (Duggal et al., 2022). The circular economy needs to be re-imagined fundamentally, with the emphasis placed on evaluating the systemic perspective in which the core purpose is to allocate resources equitably without causing damage to the environment or compromising social well-being (Velenturf and Purnell, 2021).

Through the implementation of a Circular Economy (CE) model, a sustainable business route is provided because of the maximization of the life cycle of products and their materials, thus reducing waste and efficiently utilizing resources (Geissdoerfer et al., 2017; Davari et al., 2023). The Technical combinations of blockchain technology, IoT and AI systems are witnessed to improve operational capacities of organizations as well as enhancing system defenses (Musa and Musa 2025). The traceability systems are an essential part of the process of creating closed-loop supply chains since they represent the key instruments of tracking the products, materials, and data through their whole life cycle (Gazeau et al., 2024; Santana and Ribeiro, 2022). Giovanardi et al. (2023) showed that asset traceability would provide more visibility of the supply chain, less consumption of resources in operation, more usability of the assets, and recovery to reuse building components.

The proposed research suggests the adoption of blockchain that can provide complete traceability in the systems of the circular economy (Rumetshofer and Fischer, 2023). The ability of blockchain to address weaknesses in security, fraudulent transactions, and provide unparalleled transparency makes it an innovation in the sphere of supply chains (Habib et al., 2022). Being a new technology, blockchain supports the development of competitive advantage by the innovative platform-related business models (Musa and Musa, 2025; Berdik et al., 2021; Tseng et al., 2020; Alazab et al., 2021). Musa and Musa (2025) Survey The respondents of the Survey estimate that blockchain use will emerge in the next 2-3 years with a 34.7% probability (Musa and Musa, 2025). The results indicate that the use of blockchain will accelerate by appropriate regulations and specific training courses and availability of implementation processes. The industry leaders are already testing blockchain applications as a way of exploiting its traceability and transparency advantages (Chang et al., 2022). The proposed study by Musa and Musa (2025) examines the primary blockchain benefits to supply chains and evaluates the outcomes of applying blockchain to supply chain reliability and efficiency analyzing the corresponding challenges and opportunities. The research project is aimed at offering evidence grounded implementation measures to be applied by the various Nigerian stakeholders to adopt blockchain as a real solution to their critical supply chain issues more than as experimental research.

However, many manufacturing organizations, especially those in developing countries like Nigeria, are still relying on old-fashioned, paper intensive, or centralized systems that are operationally inefficient and not secure (Okorie and Jibril, 2023). The proposed study targets and analyzes the transformational potential of blockchain by the review of limited manufacturing companies in the Southwest region of Nigeria that focus on supply chain management through traceability, mitigating fraud, and cost optimization.

2. Materials and Methods

2.1 Research Design

The research design that was adopted in this study was a quasi-experimental pre- post research design with a qualitative exploratory aspect. The quantitative part involved the comparison of key performance indicators (KPIs) of the blockchain supply chain before and after the implementation in the same manufacturing companies whereas the qualitative section involved the attitudes of the executive regarding the benefits and barriers to implementation.

The measures of the pre-implementation phase (12 months before the adoption of blockchain) and the post-implementation KPIs (12-18 months after implementation) were grounded in the condition of the system stabilization and operational learning effect. Because companies were not assigned to treatment at random, the study does not purport to have a strict causality but assesses associative and performance-based effects of blockchain adoption.

2.2 Sampling Frame and Participants

The sampling frame consisted of medium and large-scale manufacturing companies with formalized supply chains in South-West Nigeria, which were sampled by using industry association lists and state manufacturing directories.

Inclusion criteria were:

- Formal registration of manufacturing,
- Documented supply-chain operations, and
- Incomplete or complete blockchain implementation to track some aspects like traceability, recording transactions, or inventory keeping.

The pilot-only companies or those that did not have historical data on KPIs were not included. Among 210 contacted firms, 150 companies gave full and useable datasets, which gave a response rate of 71.4%. As part of the qualitative aspect, 100 senior executives (supply chain managers, operations directors, CIOs) were selected purposely based on their direct participation in blockchain adoption decisions.

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2.3 Data Collection

Quantitative data: In this study, the researchers used quantitative data collected by analyzing companies that adopted blockchain technology in managing their supply chains. The performance metrics pre and post-implementation came after the implementation of the blockchain technology. The KPIs measured includes:

- Lead time (in days)
- Operational costs (in Naira)
- Inventory tracking errors (%)
- Order fulfillment discrepancies (%)
- Traceability (%)
- Data integrity (%)
- Fraud reduction (%)
- Cost savings (%)
- Stakeholder trust (%)
- Transparency, operational efficiency, and fraud prevention scores (on a scale of 1–5)

Table 1 *Operational definition of key performance indicators*

KPI	Definition	Unit	Data Source
Lead Time	Average order-to-delivery duration	Days	ERP records
Operational Cost	Annual supply chain operating expenditure	₦ per firm	Financial reports
Inventory Errors	Mismatch between physical and recorded inventory	%	Inventory audits
Order Fulfillment Errors	Incorrect or delayed orders	%	Customer logs
Traceability	Proportion of transactions fully traceable end-to-end	%	Blockchain logs
Fraud Incidence	Documented fraud cases	% reduction	Compliance reports
Stakeholder Trust	Perceived trust score	Likert (1–5)	Executive survey

2.3.1 Qualitative Data Analysis

The semi-structured interviews with the duration of 30-45 minutes were presented through virtual meetings and face-to-face sessions. An implementation experience interview guide, organizational preparation, interoperability, cost implication, and regulatory issues.

Thematic analysis was used in the analysis of Interview transcripts. Responses were independently coded by two researchers and differences settled upon through discussion. Inter-coder reliability was more than 85%, which means that it is acceptable. Anonymized quotations were used to show the key themes with a sense of confidentiality.

2.3.2 Statistical Analysis

Quantitative data were analyzed using SPSS version 26. Paired-sample t-tests were used to compare pre-implementation and post-implementation KPIs when the variables were normally distributed and Wilcoxon signed-rank tests, when the assumptions of normality were violated (ShapiroWilk test).

Effects were also determined using Cohen's d and 95% confidence intervals. Statistical significance was defined as $\alpha = 0.01$ to minimize Type I error as a result of several KPI comparisons. Listwise deletion was performed when missing data (<3%) were present because of no systematic trend.

Since the quasi-experimental design is used, the results are viewed as performance associations rather than causal effects.

3. Results and Discussion

The comparison of the figures 1, 2, and 3 provides the key performance indicators (KPI), such as lead time, costs of operation, and error rates, before and after introducing the blockchain technology into manufacturing supply chains. The subsequent decrease in lead times is consistent with the findings of the prior studies on cooperative strategies of supply chain.

In Figure 1, Figure 2 and Figure 3, the key performance indicators (KPIs) in a supply-chain system are comparatively analyzed before and after the introduction of blockchain technology. The dataset consists of four key KPIs, such as Lead Time, Operational Costs, Inventory Tracking Errors, and Order-fulfillments Discrepancies, and quantifies the change of each of them, quantitatively, following the introduction of blockchain integration.

As shown in figure 1, lead time in the number of days is defined as the difference between the start and completion of a process which is one of the metrics that are widely used in the delivery cycles and logistics. Before the introduction of blockchain, it used to take 60 days to turn around the lead time. After incorporating blockchain, the time of lead reduced to 42 days, whereas the reduction was 30% with blockchain. This enhancement is possible due to real-time access to data, workflow optimization using smart contracts, all of which increase the speed of information flow and eliminates bottlenecks in the supply chain process (Musa and Musa, 2025).

The second measure, which is operational costs in Nigerian Naira, also reflects significant improvement. In the first scenario, the operational costs were N500, 000, 000, 000; in the latter case, the costs decreased to N375, 000, 000, 000 which is 25% lower (Figure 2). This saving is perhaps because it will reduce the number of manual processes, administrative overheads, better inventory accuracy, and reduced disputes or the need to re-do its work under the support of transparency and automation afforded by blockchain systems (Alazab et al., 2021). One of the executives said that the initial cost was difficult to justify at the beginning when there was uncertainty in terms of enterprise resource planning (ERP) integration. Another remarked that the resistance of the staff came more from fear of the unknown rather than by technical problems. Enterprise resource planning (ERP) systems are installed software platforms that harmonize and regulate the key business processes in an organization through a central database and real-time information flow through functional units. This was a systems based integrated platforms of managing production, inventory, finance, and logistics as system sources of pre and post-implementation performance data.

Figure 3 depicts inventory-tracking errors, which measure the flaws in recording and handling of inventory data and are often the cause of stockouts, overstocking, mis-allocation of deliveries, and a mismatch between order-fulfillment and orders. Until the implementation of the blockchain system, the rate of error in inventory-tracking was 8%. After the implementation the error rate was lowered to 4.8% representing an accuracy gain of 40%. The ability of the blockchain platform to offer a single source of truth and real-time synchronization of stakeholders improves inventory management since there are fewer discrepancies in the level and location of stocks.

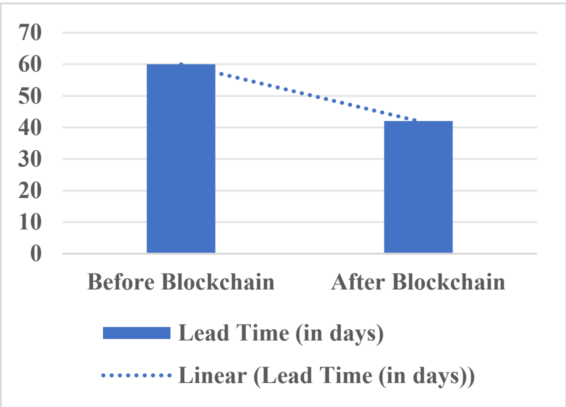

Fig. 1 *Lead time (in days)*

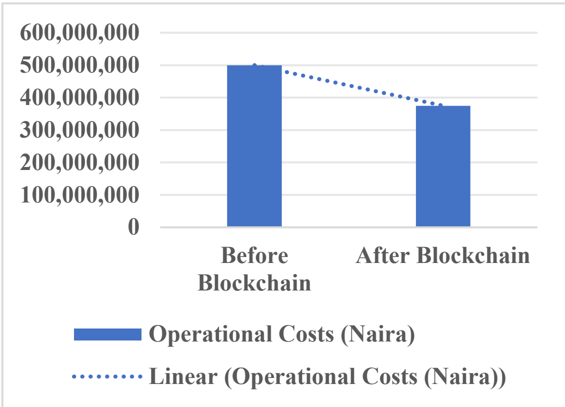

Fig. 2 *Operational costs (Naira)*

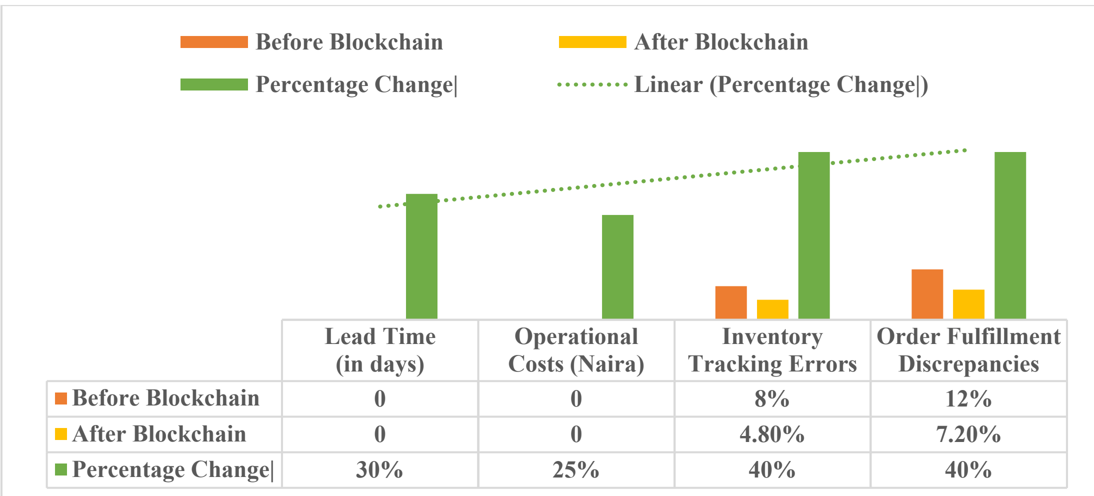

Fig. 3 *Error rates before and after the adoption of blockchain technology (%)*

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Further, order-fulfillment irregularities represent the deviations between the quantity and nature of the ordered goods and those of the customer. These discrepancies were initially observed at 12%, which means that the level of inaccuracy of order fulfillment was rather high. Following the introduction of the blockchain, the rate dropped to 7.20% - 40% lower. This advantage can be explained by the traceability capabilities of blockchain, that is, all the steps in the chain of orders, such as placement and delivery, are registered and can be audited and verified by all participants (Alazab et al., 2021).

Figure 4 compares the two sets of data that demonstrate improvement of key supply chain indicators after the blockchain technology implementation. The five KPIs considered as traceability, data integrity, reduction of fraud, reduction of cost, and stakeholder confidence are indicative of key success factors of modern supply chain management.

The traceability measure is enhanced to a higher range between 60% and 95% in the traditional systems and blockchain implementation respectively. The conventional systems are usually characterized with data silos that are discrete making it difficult to monitor the flow and source of products between various entities. In comparison, blockchain provides a decentralized and unchangeable registry that allows end real-time access to the product history and improves end-to-end visibility (Saberi et al., 2019). Greater traceability has the effect of minimizing risks of counterfeit products and making an efficient process of recall thereby enhancing supply chain visibility (Musa and Musa, 2025). The measure of data integrity makes a phenomenal improvement of 50% to 98%. The old systems of data are liable to mists due to manual input, nonconformity in formats and disconnected databases. Blockchain improves the integrity of the data by using cryptographic functions and consensus mechanisms to guarantee the data authenticity and consistency (Subrahmanyam, 2025). When a transaction is documented, it cannot be manipulated and hence, there is minimal risk of data distortion and enhance the integrity of information in making a decision (Ahmed, 2025).

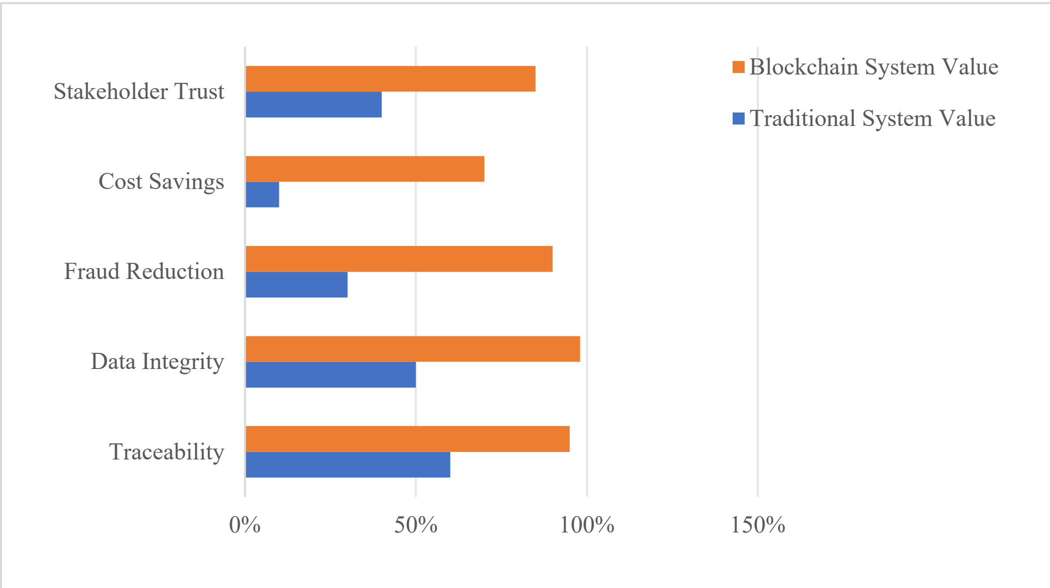

Fig. 4 *Key performance indicators (KPIs) for blockchain implementation*

The metric of reduction of fraud is shown as greatly improved, with blockchain having 90% as opposed to the traditional systems of 30%. Such an improvement is due to the open and unalterable quality of blockchain records that can make it extremely hard for bad actors to destroy records or engage in fraudulent activities without being noticed (Kshetri, 2018). In addition, all the transactions are time-stamped and auditable which allow compliance regulations to be monitored and enforced more efficiently. The savings on costs change, being a marginal 10.0 points with the traditional operation, to a sound 70.0 points with blockchain-facilitated settings. Blockchain lowers the costs of operation by automating manual operations via smart contracts, mitigating the need to use intermediaries, and also reducing the dispute-resolution period (Treiblmaier, 2018). Such efficiencies result in a tight supply-chain structure that is leaner and less costly.

A qualitative, but essential performance indicator, stakeholder trust, increases to 85% after implementation (as compared to 40% pre-implementation). With traditional supply chains, there is an absence of trust among parties due to a lack of visibility of data and poor communication. This is because blockchain encourages teamwork and trust through the transparent, secure, and verifiable records of transactions that are open to all the authorized stakeholders (Francisco and Swanson, 2018). Consequently, suppliers, logistics providers, regulators and customers find it easier to trust common data.

Table 2 *Blockchain adoption challenges*

Challenge	Frequency (%)	Description
High Initial Investment	65%	Respondents cited significant upfront costs for implementing blockchain systems
Resistance to Change	50%	Employees were hesitant to adopt new processes due to unfamiliarity.
Interoperability Issues	45%	Integration with legacy ERP systems posed technical difficulties
Scalability Concerns	40%	Executives expressed doubts about handling large-scale operations
Regulatory Uncertainty	35%	Lack of clear legal frameworks hindered adoption decisions.

In Table 2, the qualitative feedback achieved by conducting semi-structured interviews with senior executives provides an explanation of the issues that have been faced in the unity of blockchain technology. Semi-structured interviews enabled the researcher to pitch inquiry questions based on the emerging themes hence improving on the completeness and comparability of the gathered data. This table outlines the most common issues encountered throughout the implementation of the blockchain in the supply-chain setting. Evaluation of the feedbacks shows that there are five main barriers: high initial cost, resisting change, interoperability issues, scalability, and uncertainty of the regulatory environment, with each having frequency percentages that indicate the amount of this problem among organisations.

It is important to note that high initial investment has been used most often, with 65% of the respondents mentioning this. This observation shows that most organisations have found the initial expense of blockchain infrastructure such as hardware, software, qualified staff, and training cost to be prohibitive. This early investment often compels the small and medium-scale companies (SMEs) not to implement blockchain technology despite its long-term potential benefits. According to Queiroz and Wamba (2019), blockchain solutions require a large capital investment, especially when combined with enterprise systems and Internet of Things (IoT) solutions, which explains the reluctance of cost-conscious sectors. On the same note, resistance to change uses the second position, where 50% of participants noted that it is a major impediment. Managing change within an organization is a significant obstacle, particularly in the instances where the workers are not conversant with decentralized technologies or consider these to be a challenge to the usual work processes. The psychological resistance is usually due to the fear of being displaced at work or high cost of learning a new system. Saberi et al. (2019) point out that an effective implementation of blockchain is not only dependent on the technical readiness; it requires cultural change and re-skilling of the workforce, which is ignored by many organisations when developing digital strategies.

In 45% of respondents, the interoperability issues were mentioned. The challenge of the integration of blockchain systems into the current enterprise resource planning (ERP) systems and other legacy IT infrastructure was mentioned. More frequently, the traditional systems are managed centrally and do not support the decentralized reasoning of blockchain. Such inconsistency is capable of causing data silos and the impaired flow of information. As noted by Casino et al. (2019), the problem of standardization of blockchain protocols and APIs also makes the process of integrating blockchain more complex and interoperability remains a technologic and strategic issue.

Scalability issues were raised by 40% of executives and this is an indication of the uncertainty about whether blockchain can handle large-scale and high-volume operations. Although blockchain guarantees security and transparency, the consensus mechanisms (proof-of-work) might result in a lower transaction speed and decrease in throughput, as the network size grows. Yli-Huumo et al. (2016) emphasize that the majority of blockchain frameworks have performance bottlenecks that make it less adaptable to real time and high frequency supply-chain contexts especially in fast moving consumer goods and logistics.

The 35% of the respondents recognized regulatory uncertainty. The absence of well-described legal frameworks and government policies about blockchain causes confusion and risk to potential adopters. The ambiguity on compliance, data privacy, taxation, and cross-border digital transactions usually forces businesses to postpone or abandon blockchain projects. According to Kshetri (2018), legal ambiguity is among the greatest external impediments to blockchain diffusion to areas where the digital governance framework remains immature.

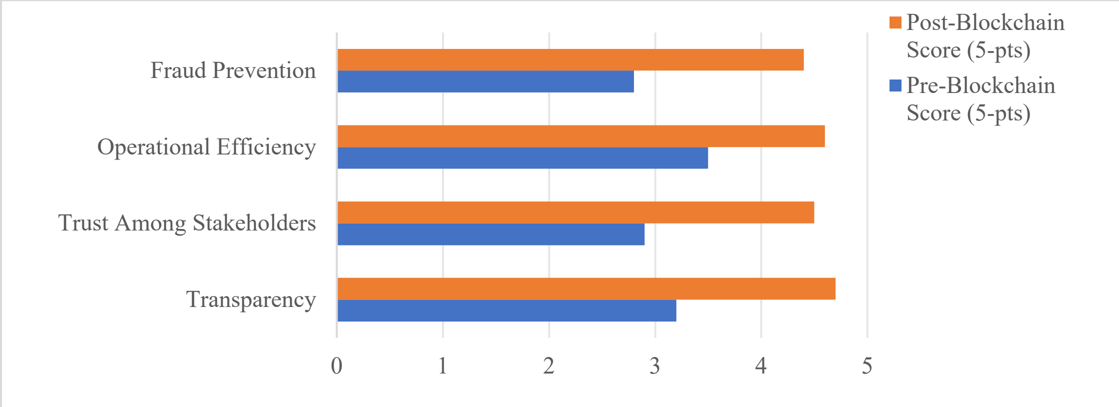

Fig. 5 *Impact of blockchain on manufacturing supply chain efficiency*

The figure 5 offers a comparative study of the main supply-chain performance indicators before and after the introduction of blockchain technology in the manufacturing industry. The paper focuses on four areas of critical concern: transparency, trust of stakeholders, efficiency of the operations, and prevention of frauds, and presents statistically significant changes of the outcomes in all four areas ($p < 0.01$), which means that it provides a high level of confidence in the results.

The transparency can be shown by a pre-blockchain rating of 3.2 out of 5, which shows the medium visibility across the supply chain. This measurement rose significantly in the post-implementation to 4.7 out of 5. The improvement evidences that blockchain technology will enhance transparency by providing real-time and mutual access to data among all the parties involved in the supply-chain. Every transaction and goods movement gets logged on a distributed ledger, thus reducing the chances of data manipulation and enhancing accountability along every supply process juncture. This significant growth is supported by the p value of below 0.01, and it is also in line with the conclusions of Saberi et al. (2019) who concluded that blockchain offers better traceability and openness to the global supply-chain networks.

Stakeholder trust had a pre-blockchain rating of a lower 2.9 out of 5, indicating the lack of confidence and cooperation between supply-chain partners. The score has increased significantly after the adoption of blockchain to 4.5 out of 5. This sharp improvement highlights the value of blockchain in creating a non-tampering record of transactions that consequently foster trust between manufacturers, suppliers, logistic provider and customers. The data integrity provided by blockchain eliminates the use of third-party verification (Francisco and Swanson, 2018). Also, blockchain has now been found to enhance inter-organizational trust in the multifaceted supply ecosystems, as reported by Francisco and Swanson (2018).

In addition, the efficiency of operations also demonstrates that the average score has improved by 0.1 between 3.5 prior to blockchain and 4.6 following blockchain adoption. This good turnover highlights the role of blockchain in automation and better coordination of data. Smart contracts reduce the number of approvals required to be done manually, and automated processes of reconciliation save time and resource wastages. This growth in efficiency is in line with Treiblmaier (2018), who has mentioned that blockchain minimizes supply-chain friction, enables improved inventory planning, and streamlines the process of decision-making.

As a result, the level of fraud prevention rose significantly, as the scores have risen to 4.4 out of 5 following blockchain implementation, compared to 2.8 out of 5 before that event. This enhancement underscores the role of blockchain in minimizing counterfeiting, unheralded modifications and other types of fraudulent conduct. Given that blockchain makes records unalterable and verifiable, it is hard to suspect that malicious actors can manipulate supply-chain data. According to Kshetri (2018), blockchain can be used as a tool against fraud in decentralized systems due to the transparency and security of the tool.

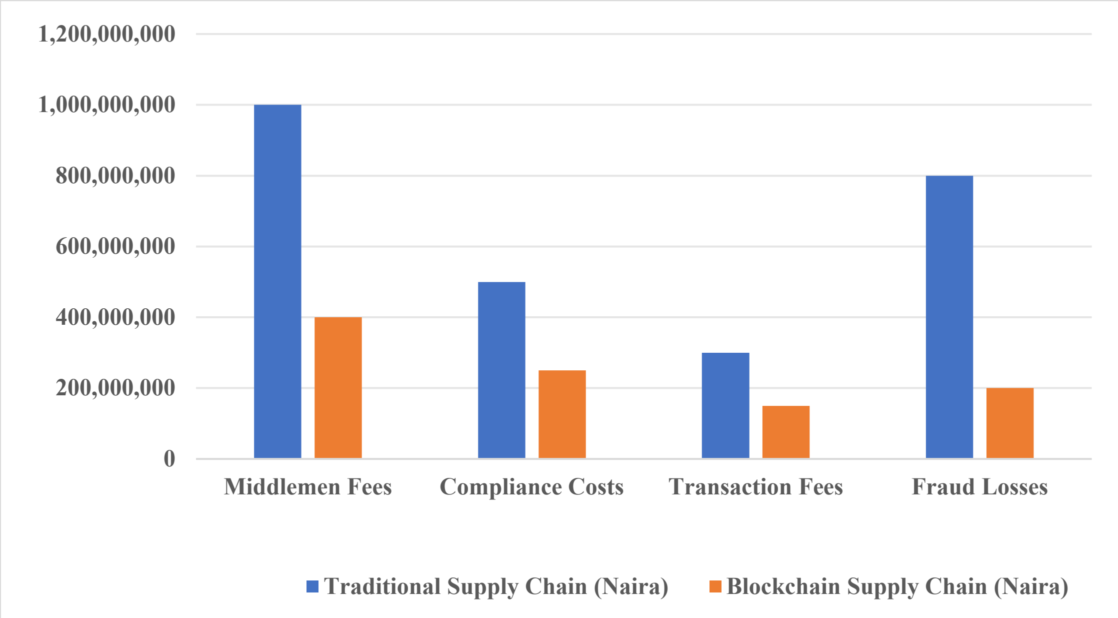

Fig. 6 *Cost comparison of traditional vs. blockchain supply chain*

Figure 6 illustrates four main cost elements including intermediary fees, compliance costs and transaction costs and fraud costs and gives the dollar estimate of the two traditional and blockchain-based supply-chain models in Nigerian naira. The numbers provide a clear indication that the application of blockchain technology results in significant cost cuts in all the considered regions with the most significant improvements being in the form of intermediary costs. A classic supply-chain set-up would cost the organizations about ₦1,000,000,000 in costs that can be attributed to intermediaries like brokers, third-party logistical, and agents. Such intermediaries are needed in a traditional system where trust and flow of information are disintegrated. Nonetheless, in blockchain, these expenses are significantly lowered to ₦400,000,000, which is a 60% decrease. This significant reduction can be explained by the ability of blockchain to build trust and directly perform peer-to-peer transactions between parties with the help of smart contracts and decentralized appearances. According to Saberi et al. (2019), blockchain improves the elimination of the use of intermediaries by introducing transparency and traceability in real-time and, as a consequence, lowering coordination and communication costs.

The cost of intermediaries is not the only type of costs that is to be decreased through the implementation of blockchain; the compliance costs also decrease greatly. Conventional systems cost the organization about ₦500,000,000 in regulatory and documentation-related fees, which is usually created through manual operations and disjointed data sources requiring human forstall and audit. On the contrary, the blockchain systems reduce these costs by 50%, and they are reduced to ₦250,000,000. The resulting cost efficiency is due to the immutability and time-stamped nature of blockchain records that makes regulatory reporting and audit trails simpler and less man-intensive. According to Treiblkeyer (2018), the automated and verifiable quality of the entries into blockchain makes the process of complying with all industry standards and legal requirements much smoother.

Lastly, in the traditional supply chain, transaction costs typically cost approximately N300, 000,000 to handle payments and record keeping in financial institutions or clearances. Such charges can be attributed to the poor efficiency when it comes to verifying, reconciling and settling payments in a variety of platforms. Blockchain technology will cut the transaction cost by 50% to ₦150,000,000,000 which will translate to 50% cost reduction.

All these savings can be explained by the removal of unnecessary verification procedures, payment packets carried out directly using smart contracts, and the need to reduce the number of third-party interventions. This benefit has been widely mentioned in the scholarly literature, and Francisco and Swanson (2018), in particular, highlighted that, due to the blockchain technology, payment friction and processing costs are reduced along world supply chains.

Fraud-induced losses constitute a hidden though significant monetary leak within the traditional supply chains with an estimated fraud drain of ₦800,000,000. Such losses are majorly due to counterfeit products, data falsification, and manipulation of data. The blockchain-based systems reduce the losses caused by fraud to ₦200,000,000, which is 75% less. The fact that blockchain is a mandatory ledger that cannot be changed also makes alteration of the transaction histories virtually impossible, as they should be noticed. As Kshetri (2018) explains, this resistance to tampering is a very important feature to improve the safety of the supply chain and help organizations to prevent the emergence of fraudulent actions that may result in serious financial punishment and a significant loss of reputation.

Table 3 *Heuristic optimization outcomes for blockchain implementation*

Optimization Objective	Initial Value	Optimized Value	Improvement (%)
Production Lead Time	12 hours	8.4 hours	30%
Resource Utilization	70%	85%	21%
Energy Consumption	500 kWh	420 kWh	16%

Table 3 shows the results of optimizing the blockchain implementation in the key production metrics. Three optimization goals, namely, production lead time, resource use, and energy consumption, were analyzed. These measurements are used to gauge the efficiency of a production system in its entirety and its sustainability. Each objective has been analyzed in detail in the following sections.

The original lead time of production was 12 hours and the lead time after optimization reduced to 8.4 hours, which is a 30 per cent cut. This great enhancement shows that blockchain-mediated optimization was critical in ensuring that the production process was simplified (Vettriselvan et al., 2024). Blockchain will help to reduce inefficiencies by providing real-time information and increasing transparency in the production chain (Musa and Musa., 2025). With better coordination and removal of delays that can be attributed to miscommunication, speedy production cycles are realized which eventually result in quicker product delivery and increased operational agility (Ahmed, 2025).

The efficiency of using resources increased by 41% as the percentage of resources utilized rose by 21%. This shift shows that blockchain optimization helped to make the utilised resources such as labour, machinery, and materials more efficient. The ability to track and control resources in real time provided by blockchain helps to prevent the over-use of resources and their under-utilization as well (Vettriselvan et al., 2024; Tapscott and Tapscott, 2017). Blockchain offers a clear and permanent history of resource allocation to maximize the utilization of assets, which will minimize waste and improve asset management (Saberi et al., 2019). This enhancement of resource usage is therefore an important factor of higher productivity as well as lower cost of operation.

The consumption of the energy was reduced to 420 kWh as compared to 500 kWh, and it gave a 16% decrease in the energy consumption. This reduction is consistent with larger sustainability goals, where energy optimization reduces the cost and alleviates environmental effects of production processes (Zehra et al., 2024). The capabilities of the blockchain to track the consumption trends in real-time make it applicable to the energy optimization process as it allows the efficient energy distribution and load balancing (Kshetri, 2018). Blockchain eliminates energy wastage, with these gains benefiting the economy and environment. In addition, blockchain-supplied real-time information can detect the inefficiency of using energy, and specific energy-saving solutions can be implemented (Yang et al., 2025; Khan et al., 2025).

The general results highlight the effectiveness of blockchain implementation in streamlining the production systems. The possibility of utilizing blockchain as a transformational instrument in the manufacturing and industrial processes is highlighted by the fact that it is able to boost the speed of the process, increase resource use, and make the processes more energy efficient. Such advances support the studies by the past that show blockchain enhances the efficiency and sustainability of operations (Musa and Musa, 2025; Saberi et al., 2019; Kshetri, 2018). Blockchain increases productivity and provides cost savings as well as ensures environmental sustainability by reducing production lead time, optimizing resource allocation, and reducing energy consumption.

Table 4 *Comparative analysis of blockchain and traditional systems*

Feature	Traditional System	Blockchain-Based System	Advantages of Blockchain
Data Immutability	No	Yes	Prevents tampering and ensures trustworthiness.
Real-Time Tracking	Limited	Fully Enabled	Enhances visibility across all supply chain stages.
Cost Efficiency	Moderate	High	Reduces intermediaries and operational redundancies.
Compliance Monitoring	Manual	Automated	Simplifies audits and regulatory adherence.

Table 4 compares the traditional information systems to the blockchain-based systems, with the focus on four critical attributes, including data immutability, real-time tracking, cost efficiency, and compliance monitoring. The attributes are essential in measuring the effectiveness of every system, especially in areas of supply-chain management, finance and logistics.

The traditional systems do not often offer assurances of immutability of data, they can be changed or compromised once the information is entered into the system. This weakness is an important threat to use in the areas where accuracy of information is crucial like in finance and legal records. By comparison, blockchain-based systems uphold data immutability so that once data is stored in the blockchain, it cannot be modified or destroyed. This aspect has rendered blockchain particularly beneficial in fraud prevention and building the credibility of data and, in general, improving the security and dependability of records in areas where integrity is a significant factor, including financial operations and supply-chain tracing (Hossain et al., 2024; Ogunyankinnu et al., 2022).

Conventional systems are usually limited in real-time tracking features, which are based on databases or manual reporting mechanisms, which may cause delays and limited visibility of a process through its stages. In contrast, blockchain-based systems permit full real-time tracking through entries of all transactions on a distributed registry that all network actors could see. This structure brings about enhanced transparency and real-time information to all stakeholders hence enabling them to make better decisions, to respond faster, and to operate more efficiently. Within supply chains, e.g., the given feature will minimize fraud and guarantee proper tracing of goods on their way to the consumer, thus, making the process of scanning them more transparent (Tapscott and Tapscott, 2017).

Conventional systems are moderate in cost efficiency and money transfer or payment usually involves a middleman like brokers, banks and verification of third parties to take place and to keep all secure. Such intermediaries add overheads on cost and administration. However, blockchain-based systems are even more cost-effective, as they get rid of intermediaries and decrease redundancy in operations. Blockchain reduces the third-party intervention and expenses related to it as it allows direct peer-to-peer transactions via smart contracts and automatization of operations. The subsequent optimization of the workflow and the automatization of the functions that would otherwise require human intervention reduce the transaction and operation costs which facilitates better use of resources and end up saving money (Kshetri, 2018).

The monitoring of compliance of traditional systems is mostly manual in nature which requires audits and regulatory checks to ascertain that the legal and industry standards are adhered to. This method is usually time consuming, prone to errors and inefficient, particularly, when dealing with complicated supply chains or complicated regulatory requirements. Stand alone blockchain powered systems, however, provide automated compliance checks through smart contracts. Such self-executing contracts incorporate terms and conditions of a contract into a coded form and automatically ensure that all parties adhere to the agreed-upon terms and regulatory standards in real time. Consequently, blockchain will make the audit process easier and keep the regulatory compliance, which significantly decreases the possibility of human errors and improves the overall compliance performance (Saberi et al., 2019).

Table 5 *Comparison of traditional and blockchain-based supply chains*

Feature	Traditional Supply Chain	Blockchain-Based Supply Chain
Data Integrity	Prone to manipulation	Immutable and transparent
Transparency	Limited visibility	End-to-end traceability
Fraud Prevention	High risk	Reduced risk through smart contracts
Cost Efficiency	High due to intermediaries	Lower due to automation
Real-Time Tracking	Delayed updates	Instant and continuous tracking

Table 5 contains the comparison of the traditional and blockchain-based supply chains according to 5 main characteristics: Data Integrity, Transparency, Fraud Prevention, Cost Efficiency, and Real-Time Tracking. They are features that are crucial in the evaluation of the effectiveness of a supply chain system especially in industries that need accuracy, security, and efficiency.

Data security is often jeopardized in the traditional supply chain as central databases and manual methods are used, which allows any errors, fraud, and discrepancies. Information is easily distorted or compromised through hacking at any point during the supply chain and poses a very big threat. In comparison, blockchain supply chains offer transparent and impossible to amend data; once an operation is stored on the blockchain it cannot be changed or erased, which guarantees the quality and reliability of the information. This renders blockchain an effective approach to the industry in which the quality and dependability of information is paramount like pharmaceuticals and financial services (Kshetri, 2018).

The old supply chains are also characterized by low visibility since the information is often isolated and hidden in the various parties and systems. Such a lack of transparency may result in the inefficiency and slowness in decision making. Conversely, supply chains based on blockchain will have end-to-end traceability, meaning that overall visibility of products can be seen regardless of the location of goods. Blockchain documents each supply chain action on a decentralized registry, so that every stakeholder is able to access transparent and real-time information. This increased transparency improves the trust between the partners of the supply chain and promotes the process of better coordination and decision-making (Tapscott and Tapscott, 2017).

Another aspect in which blockchain is superior to the traditional systems is in fraud prevention. Fraud is very susceptible to traditional supply chains because supply chains require intermediaries and there are no safe and transparent records. The tampering of invoices or misrepresentation of shipment is a typical action of fraudulent activities since the system is likely to be subjected to human error and manipulation. Conversely, blockchain can be used to reduce the chances of fraud by a significant margin because its smart contracts ensure that the terms of contracts are automatically enforced and implemented by parties. Smart contracts have ensured that transactions are not finalized unless the set conditions are fulfilled, and a procedural history is immutable, and it is practically impossible to change the history of transactions without detection on the blockchain. This significantly decreases the risk of fraud and increases the supply chain security level as a whole (Saberi et al., 2019).

Conventional supply chains are usually expensive because they involve a number of intermediaries like brokers, banks and third party verification services. These middlemen create administrative overheads and cause delays in processes, which increases the overall cost of the supply chain. Supply chains based on blockchain, however, are more cost-effective with no mediators and automatizing most operations using smart contracts. Blockchain allows the interaction between parties directly and without an intermediary; the middleman is removed, which will also reduce the costs of manual processing and compliance checks, as well as transaction verification. The blockchain makes supply chains more cost-effective and assists companies with minimizing administrative costs by automating the main supply chain actions (Kshetri, 2018).

Therefore, real-time monitoring in conventional supply chains may be postponed due to the use of manual systems and central databases, which may cause discrepancies and slow updating. The monitoring of goods or inventory usually entails waiting to get information updated in different systems and this attribute causes delays and inefficiencies as well. Conversely, blockchain allows tracing goods along the supply chain in real-time and any time by registering all operations in real-time on a distributed registry where all participants have access. This real-time availability of information helps to make decisions faster, better inventory management, and better logistics. Real-time tracking also means that the stakeholders will be able to respond quickly to any stockouts or shipment delays to improve the overall efficiency of the operations (Tapscott and Tapscott, 2017). One of the main aspects of reducing the lead-time variability is the feature of blockchain to enable real-time access to verified data. A collection of those figures and tables facilitates the findings of the study by providing both quantitative and qualitative measurements and comparative analyses, which prove the potential transformations of blockchain technology in manufacturing supply chains. Figure 1 to Figure3 are a clear indication of the positive effect of blockchain technology on the performance of the supply chain. All KPIs improved dramatically upon blocking the implementation of the blockchain, and the lead time was decreased by 30% and operational costs by 25%, and the error in inventory tracking or differences in order fulfillment were also reduced by 40%. These findings highlight the usefulness of blockchain as a disruptive technology to make supply chain activities more efficient, transparent, and reliable (Oriekhoe, 2024). Figure 4 illustrates how blockchain has transformational effects on the performance of the supply chain. The transition of the traditional to the blockchain systems is associated with the percentage improvements of between 35% and 60% in the most significant KPIs. These efficiencies affirm results in the recent literature, as blockchain is uniformly defined as strategic facilitator of supply chain management traceability, security, and efficiency (Saberi et al., 2019; Casino et al., 2019; Kshetri, 2018). The data sets in Table 4 indicate that although blockchain has a transformational potential, several factors affect its adoption, which comprise economic, technical, organizational, and legal issues. The most influential obstacles are high requirements of capital (65%), internal resistance (50%), and incompatibility with the legacy systems (45%), which demonstrates a necessity to do strategic planning, government support, and international standardization to help the process of wide adoption. These results are consistent with the entire academic opinion that the implementation of blockchain is not a technical project but a multidimensional initiative that must be coordinated among stakeholders, systems, and regulatory spheres (Mustafa et al., 2025).

In all the four supply chain elements shown in Figure 5, the improvements of the blockchain technology are provable concerning the numerical values of the improvement and the statistical significance of the improvement. In both scenarios, the p-value is smaller than 0.01, which means that the improvements observed can hardly be explained by random variation and can be, therefore, fairly attributed to blockchain adoption. This empirical fact confirms the claim that blockchain is an efficient enabler of efficiency, trust, security and transparency in manufacturing supply chains.

Figure 6 presents strong evidence that the deployment of blockchain may result in significant cost savings in the supply-chain management. There are 50% - 75% in savings in the top spheres, which are fees of intermediaries, compliance, transaction costs, and mitigation against frauds. Not only do these cost savings help to improve financial performance, but they also help to increase operational resilience by automating processes and increasing the level of trust, as well as intensifying a sense of security. The given observations resonate with the available body of literature according to which blockchain may be viewed as a revolutionary mechanism that can help to remove inefficiencies and contain expenses in multi-stakeholder settings (Salim et al., 2025).

The findings presented in Table 3 demonstrate the significant benefits of the blockchain adoption in the production systems. Blockchain technology can increase the economic and environmental output of manufacturing processes by reducing the length of production lead-times, resources use, and energy use. Our results are consistent with the expanding body of research that blockchain has the potential to promote efficiency, sustainability, and cost-effectiveness in the industries (Zhang et al., 2020; Yang et al., 2025). The scaling of these results to different industry sectors and long-term effects of blockchain-based optimization on the performance of a production-system should be explored in the future. The heuristic optimization strategy was useful in fulfilling two goals, that is, reducing lead times and enhancing resource allocation (Biswas et al., 2025).

As it can be seen in Table 4, blockchain-based systems have a number of advantages in comparison with conventional systems. Blockchain promotes the impossibility of data changes, real-time tracking, high cost-efficiency, and automated monitoring of compliance and can be a potent tool in improving the security, transparency, and efficiency of the working process. Blockchain technology brings more trust, cost reduction, and operational efficiency by removing intermediaries that increase visibility and simplifying compliance. With the maturity of blockchain technology, it can be seen that it can be used to revolutionize the traditional system in various industries.

However, the comparison between traditional and blockchain supply chains represented in Table 4 demonstrates the outstanding advantages of the blockchain technology in terms of increasing reliability, transparency, and efficiency. Blockchain provides end-to-end traceability, integrity of data immutability, risk of fraud reduction, automation of costs, and real-time tracking, which makes it a potent supply-chain management instrument. These are the benefits that make blockchain a perfect tool to modernize the supply chains and enhance operational power. With the further development of blockchain, its usage is likely to be increased in industries where security, transparency, and efficiency of supply-chain management are paramount. The results support the claim that blockchain technology can enhance the supply-chain transparency in the manufacturing sector significantly.

This paper suggests a blockchain-based supply chain architecture with five levels:

- Actors Layer- manufacturers, suppliers, logistics providers, regulators.
- Layer of Data Capture Layer, IoT, ERP, transaction records.
- Blockchain Layer Distributed ledger, consensus, smart contracts.
- KPIs (traceability, cost, fraud, trust) Performance Layer.
- Governance Layer compliance, auditable, regulation compliance.

The framework presents the manner in which supply chain actors create operational data that are captured by using the ERP and internet of things, secured by blockchain infrastructure, and translated into automated execution, governance, and quantifiable performance results (figure 7).

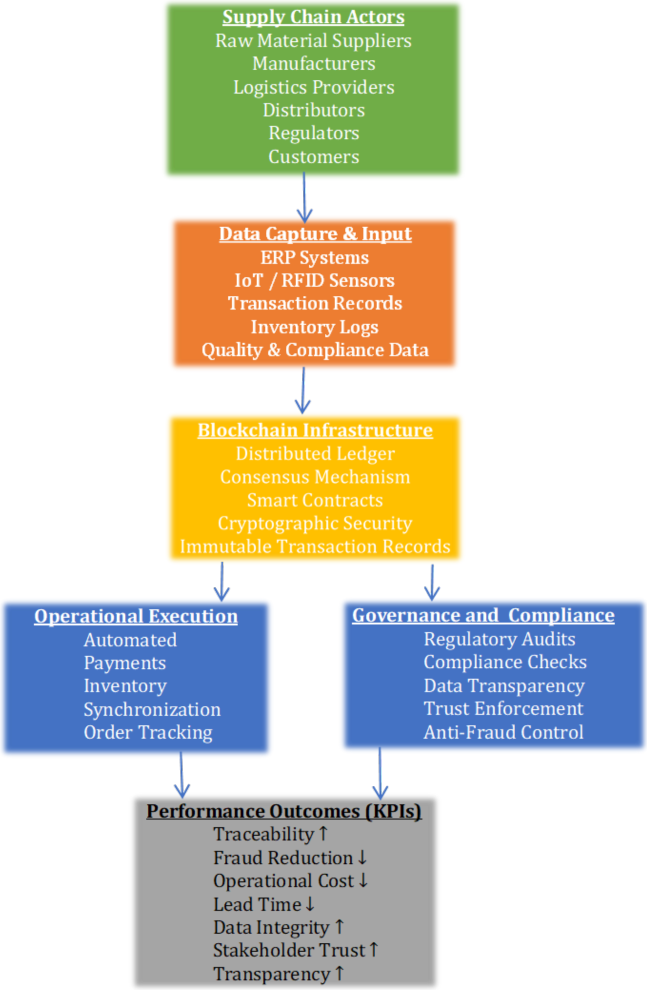

Fig. 7 *Blockchain-enabled supply chain visibility & traceability framework*

Figure 7 shows the suggested supply chain framework with blockchain infrastructure which shows how the data was gathered by various actors and secured it by blockchain infrastructure and transformed them into quantifiable changes in traceability, fraud prevention, cost reduction, and trust among stakeholders, which were found to be observed in this study. The empirical results indicate quantifiable improvements associated to every layer especially in traceability, mitigation of fraud, and cost efficiency.

4. Conclusion

The blockchain technology is a revolutionary method of improving transparency in manufacturing supply-chain. Empirical data shows that blockchain is noted to enhance transparency and has real-time and tamper-proof transaction records and product movement logs. Some of the most successful businesses have used blockchain to track the supply chains of food, which eliminates the chances of contamination and guarantees authentic product quality (Bosona and Gebresenbet, 2023; İndap and Tanyaş, 2023). Besides, blockchain reduces the use of middle-men, which results in cost-saving and increased operational effectiveness. Smart contracts computerize processes like payment checks and compliance audits, thus, reducing human mistakes and time wastage (Casino et al., 2019). However, the obstacles such as lack of scalability, great amount of energy, and regulatory uncertainties hinder its mass adoption. Nevertheless, blockchain solutions have yielded better stakeholder trust and operational efficiency in firms that have implemented it despite the challenges.

The benefits of blockchain technology are high, and especially when it comes to eliminating inefficiencies and building trust in manufacturing supply chains. The results support the transformative nature of the technology to solving deep-rooted problems in these chains. With blockchain, the information asymmetry, and the reliance on intermediaries are erased by offering verified information in real-time. However, there are still challenges like high startup costs of the systems, staff resistance to change, and interoperability with the old systems. Although the quantitative measures show their improvements are measurable, qualitative feedback shows that there is concern regarding scalability and regulatory uncertainties which might limit mass adoption. Organizations should also invest in wide-ranging employee training programs and liaise with technology providers to come up with scalable and interoperable solutions to make the most out of it. It is encouraged that policy makers should come up with clear directives and rewards that will encourage the uptake of blockchain within varied sectors. Future studies more into hybrid blockchain models that can balance both scalability and security should be conducted, which will enable the manufacturing industry to adopt it more widely. Similarly, longitudinal studies are advised to conduct studies on long-term effects and also to determine case studies in diverse geographic settings to confirm these results. Besides that, the current research suggests the use of heuristic optimization methods to overcome production bottlenecks and better resource allocation in blockchain-powered supply chains.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Adekunle Ibrahim Musa, Ayomide Idris Musa;* ***data collection:*** *Adekunle Ibrahim Musa, Ayomide Idris Musa;* ***analysis and interpretation of results:*** *Adekunle Ibrahim Musa;* ***draft manuscript preparation:*** *Adekunle Ibrahim Musa, Kapil Chaudhary. All authors reviewed the results and approved the final version of the manuscript.*

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