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Original Article

Blockchain Integration in Supply Chain Management: A Multi-Level Framework for Enhancing Transparency and Traceability

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ABSTRACT: *Blockchain technology is being seen more and more as the answer to problems related to transparency and traceability in supply chains today. The data used in these systems tends to be incomplete, and several inefficiencies exist, resulting in a high risk of fraud. Therefore, there has to be a strong structure that unites everyone and secures all aspects of the process. The Multi-Layered Blockchain Architecture combines public and private blockchains to ensure strong data integrity, security and interoperability among members of the supply chain network. Role-Based Access Control (RBAC) and Cross-Blockchain Oracles are integral to the system, enabling precise control over who accesses data and facilitating seamless communication between different chains. Smart contracts streamline jobs such as buying supplies, managing stocks and checking rules, thus lessening paperwork and mistakes by staff members. Because the ledger cannot be changed, it becomes easier to track shipments, verify origins and source goods responsibly in pharmaceuticals, car manufacturing and farming. Although AI plays a significant role, it must navigate obstacles such as high implementation fees, difficulties in connecting to older systems, and changes in laws and regulations. Research evidence indicates higher efficiency, lower spending, and improved risk management, particularly for large international supply chains. Enhanced predictive analytics and swift decision-making occur when the framework supports the Internet of Things (IoT) and Artificial Intelligence (AI). In the future, emphasis will likely be placed on making supply chains more scalable, sustainable, and open to collaboration between various industries, which should make the system more robust and resilient.*

KEYWORDS: *Blockchain technology, Supply chain management, Transparency, Traceability, Multi-layered architecture, Smart contracts, IoT integration, Data security, Operational efficiency, Sustainable practices.*

1. INTRODUCTION

1.1. THE IMPERATIVE FOR SUPPLY CHAIN MODERNIZATION

Global supply chains are becoming increasingly intricate due to globalisation, the rise of regulations, and consumers' growing demand for ethically produced products. Using manual methods and relying solely on large databases, traditional systems struggle with data splitting, slow messaging, and the risk of counterfeit products. The pharmaceutical sector loses $200 billion annually due to counterfeit medicines, and the food sector struggles with traceability as people increasingly prioritise sustainability. [1-3] Because legacy systems do not communicate well, this prevents agencies from acting promptly and being responsible. As a result of these problems, companies may experience more recalls, have to deal with non-compliance and suffer from a negative reputation, which is why a change to better, decentralized and auditable methods is important.

1.2. BLOCKCHAIN'S TRANSFORMATIVE POTENTIAL

Blockchain technology has become a major disruptor since it provides decentralization, enhanced security through encryption and permanent record storage. It is designed to ensure that suppliers, manufacturers, logistics providers, and regulators each have only one accurate source of information, which reduces issues and boosts trust. In the automotive and agricultural industries, firms that switched to automated workflows and fraud protection saw a 30–40% reduction in costs. Existing versions of blockchains mostly either ensure transparency or privacy, but struggle to maintain both qualities. It demonstrates the requirement for hybrid models that strengthen how an organization grows, how it is governed and how it works with different teams.

1.3. TOWARD A MULTI-LEVEL FRAMEWORK

A blockchain structure designed for use with various businesses in the supply chain. The design uses permissioned (private) blockchains for keeping sensitive data safe and public chains for publishing open information and links these through Cross-Blockchain Oracles. RBAC keeps data secure, and the rules for purchases, quality control, and payments set by smart contracts help keep disputes to a minimum. Using IoT sensors, the ledger now receives real-time data (for example, temperature and location) that helps predict inventory issues and associated risks. Initial research in electronics manufacturing shows a 25% improvement in the time taken to deliver and resolve recalls, over 90% faster. By addressing issues related to the integration and scalability of tools and data, the framework enables sustainable and robust supply chains that align with the objectives of Industry 4.0.

1.4. SUPPLY CHAIN CHALLENGES

Challenges encountered in the old supply chain systems and how they can lead to further hardships. The highest point focuses on highlighting major concerns, for instance, the use of centralized systems, unclear process details, compatibility issues and small-scale IoT device use. Such challenges in systems create significant effects, including difficulties in building trust, reduced visibility of supply chains, compromised safety of goods, and lower performance. The results of these effects are shown at the bottom of the diagram, for example, as customers providing poor feedback, engaging in fraud or counterfeit goods, and experiencing data loss or compromise. In this way, problems with the technology can cause damage to a company's operations and reputation. It clearly explains why blockchain is important in today's supply chains. It helps justify the main issue and the purpose of your paper. Highlighting gaps in the current approach demonstrates the need for a different approach. Notably, the main issue of having no traceability can be addressed by blockchain through the creation of a shared and secure transaction log.

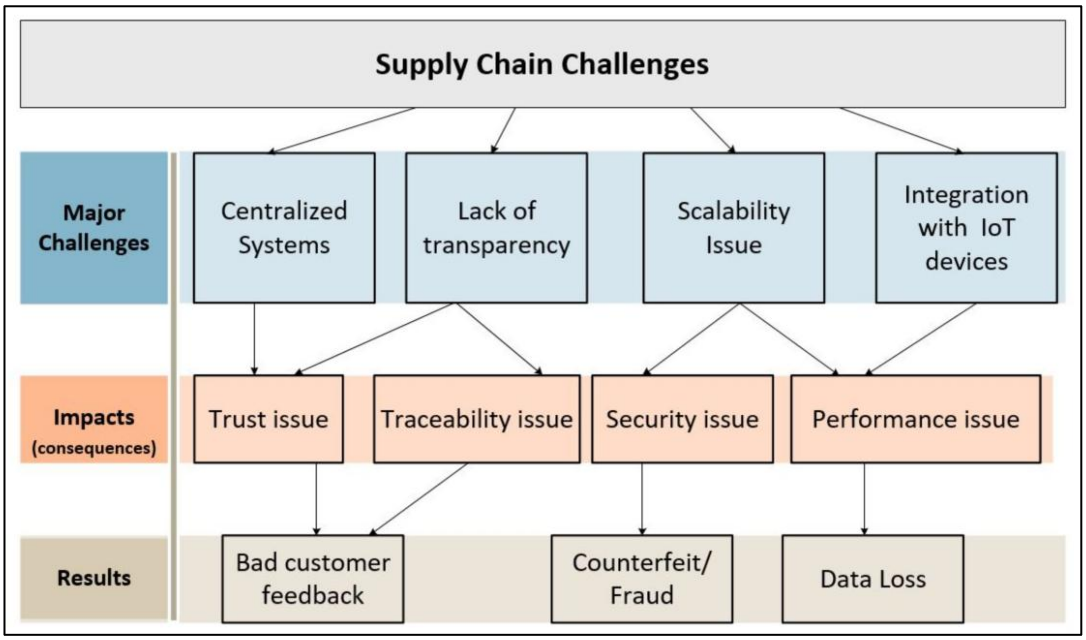

FIGURE 1 Challenge, impacts and risks in supply chain management

2. RELATED WORK

2.1. BLOCKCHAIN APPLICATIONS IN SUPPLY CHAIN MANAGEMENT

Blockchain technology is being extensively investigated for its support of supply chain operations, particularly in areas such as efficient traceability, enhanced transparency, and automation. The first applications were used in the pharmaceutical and food industries, as proving the origin of products is crucial in these fields. [4-6] For example, using blockchain technology lowers the number of counterfeit drugs, as drug journeys leave no room for tampering in the records. Blockchain, as employed by IBM Food Trust in the agriculture industry, enables the tracking of produce and reduces recalls in cases of contamination by 90%. Smart contracts are used by the automotive sector to speed up the purchasing process and ensure quality, resulting in a 30–40% decrease in administrative costs.

Sensors in the IoT network now transmit data, such as temperature and location, directly to blockchain ledgers, improving real-time tracking. Stakeholders on public blockchains (like those on Ethereum) can view transaction details, which isn't possible for private blocks designed for enterprise data. Hybrid types of architecture are still not widely explored, as most developers focus on creating systems that are either very open or very private. There are issues with scaling for public chains: they only facilitate 15–30 transactions every second, compared to private chains, which can reach 1,000+ TPS but do not connect. Although there are a few gaps, case studies demonstrate that blockchain is capable of reducing fraud and streamlining audits, while also supporting sustainability, for example, by tracking carbon emissions in fashion supply chains.

2.2. TRANSPARENCY AND TRACEABILITY IN LITERATURE

Studies indicate that transparency and traceability are basic requirements for supply chains to be sustainable and strong. Experts link these aspects to higher customer trust, strict adherence to rules, and effective risk management. Nestlé applied blockchain to their coffee system by including QR codes. According to IBM's research, as a result, 71% of customers are willing to pay a premium for these brands. Standardized data environments are the focus of such theories, which have GTINs and IoT connecting and synchronizing what each stakeholder knows.

Technology and the way organizations function are mentioned as key barriers in the literature. It was shown in Tredence's STRIVE program that handling data from several unconnected platforms while ensuring privacy was challenging. Reviewed documents indicate that there are insufficient common metrics for sustainability reporting, which makes it challenging to compare companies across different fields. The usefulness of block chain for transparency is compromised by its reliance on data that may be incorrect or deliberately manipulated by users. Additionally, as block chain ensures immutability, integrating legacy ERP and CRM systems requires creating an interface, as their API compatibility is typically lacking.

2.3. LIMITATIONS OF EXISTING APPROACHES

Block chains are currently being utilized, but they face significant technical and financial challenges. Ethereum and other public networks are experiencing significant delays and increasing transaction fees due to their inability to keep pace with large volumes of activity. Hybrid models aim to provide fast and reliable transactions, yet they require expensive oracles, which in turn make the infrastructure more complex. SMEs are not able to start using these platforms, as hiring a developer and connecting all the systems can be very expensive and sometimes exceeds $500,000.

Legacy system tools are also adding complications to cloud computing. Most supply chains still depend on software that conflicts with the decentralized design of block chain, so they need expensive middleware services. Data silos persist, as demonstrated by Schneider Electric's STRIVE program, which necessitated the manual compilation of supplier certificates from different regions. Following many rules at once can be confusing, as the EU's Green Deal, which emphasises sustainability, has guidelines that go further than those required by other parts of the world.

Errors can occur when incorrect data is placed into the system. Walmart's use of blockchain for leafy greens was a success, but it required suppliers to undergo rigorous training to prevent errors caused by IoT sensors. For these reasons, there is a need for innovative systems that manage expenses, facilitate growth, and coordinate people and technology.

3. PROPOSED MULTI-LEVEL FRAMEWORK

Illustrates how a blockchain-based supply chain management system is organized, highlighting blockchain as the main ledger that joins all stakeholders. The Supplier sends goods to the Producer, who then supplies the Distributor, who in turn supplies the Retailer, and the Retailer gives them to the Customer. [7-11] Each time data is validated, it is recorded on the blockchain while smart contracts automatically carry out the business rules. This shows one of the main advantages of decentralization. Conventional systems lock data behind each participant's security, but on a blockchain, every entity interacts with everyone else using a shared ledger. Raw materials are tracked by suppliers, who pass the data on to producers, who then monitor the finished products. All downstream players contribute their transaction records, ensuring full transparency and accountability.

Smart contract technology in block chain ensures that transactions are approved automatically without delay, eliminating the need for a middleman. Delivery confirmation by the distributor could trigger the release of payment to the producer. The automation leads to higher trust because disputes over logistics, quality and schedules are common in many industries. Chains of blockchains are illustrated to explain how participants in a supply chain are securely and transparently linked. It lays out the technical details of how your model handles and safe-keeps real-time product data and transactions.

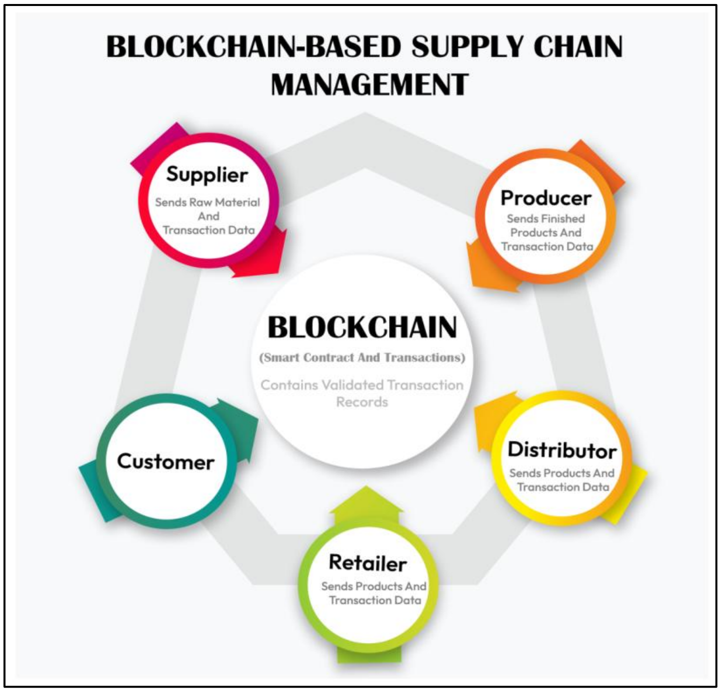

FIGURE 2 **Blockchain-based supply chain management**

3.1. OVERVIEW OF THE FRAMEWORK ARCHITECTURE

This multi-level plan was developed to address key issues in supply chain management, including transparency, traceability, and enhanced efficiency. This system uses distinct layers that are connected and responsible for particular tasks that allow data to flow conveniently and securely within the organization. The main concept is to use a decentralized blockchain ledger to produce a joint record of all supply chain actions, so every transaction and bit of data is transparent and safe. The use of private and public blockchains ensures a good balance of privacy and openness in the network.

Data Acquisition and Validation is the first phase, which gathers data from a range of sources, including IoT devices, enterprise systems, and manual typing. Now, validated data is recorded on the blockchain using the blockchain integration layer, which provides constant traceability and automates various processes through the use of smart contracts. The design of the architecture supports working alongside old systems and easily expanding as requirements change. Cross-chain communication protocols are used in conjunction with middleware to enable seamless data transfer between blockchain systems and traditional IT systems. Using this holistic approach reduces resource waste, limits supply chain risks, and helps create strong strategies by ensuring all information is up to date.

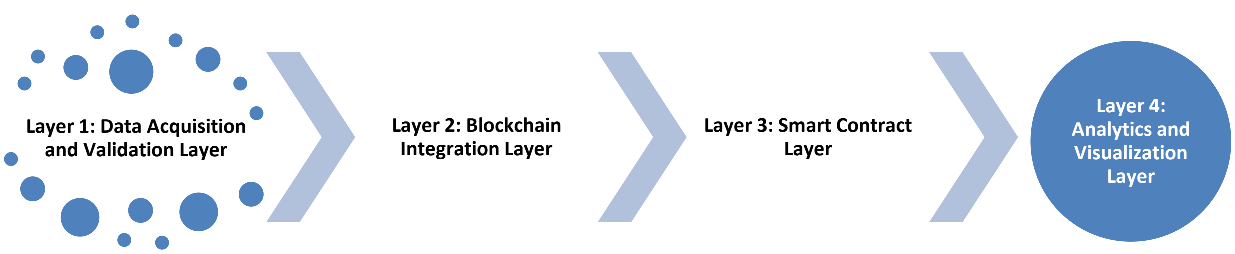

FIGURE 3 **Blockchain-enabled supply chain process**

3.2. LAYER 1: DATA ACQUISITION AND VALIDATION LAYER

The initial step in the framework focuses on detailed data collection and strict validation to ensure the accuracy of the information used in blockchain. Data is collected from multiple endpoints, including environmental sensors, inventory systems, and personnel responsible for managing the supply chain. Monitoring goods in real-time and obtaining details such as temperature, humidity, and location is especially important in the food and pharmaceutical sectors, so connecting these devices with IoT is crucial. The framework prevents poor outputs by using automated verification systems and consensus-based tools. Multiple sources verify and compare the data before it is added to the blockchain, making it more difficult for someone to make a mistake or add fake information. Advancements in both analytics and AI can spot any problems or questionable actions among the data, making it even more reliable. Data standardization in this layer means that information is formatted the same way across various systems and stakeholders, which is key for effective sharing and further processing. Strongly building this trusted data layer enables other blockchain processes to function effectively and securely.

3.3. LAYER 2: BLOCKCHAIN INTEGRATION LAYER

This is the central section where approved data is registered safely on the blockchain. Depending on the type of data being shared, this layer utilises either permissioned or permissionless types of blockchains. [12-15] For private business transactions or sensitive data, permissioned blockchains are chosen, providing access only to participants with permission. In this case, permissionless blockchains make certain data visible, helping to develop trust among people outside the company and its consumers.

Since smart contracts automate essential processes, including procurement, payments, compliance, and dispute resolution, they are crucial in this area. Such contracts ensure that all transactions occur under a set of predefined terms, thereby reducing the chances of errors and conflicts. It uses protocols for cross-chain connectivity and additional middleware to allow blockchain networks to be used together, which tackles a significant barrier to using blockchain more broadly. Because it records all actions in the supply chain, this layer enhances traceability, accountability, and efficiency, while also helping to meet regulations and prepare for audits.

3.4. LAYER 3: SMART CONTRACT LAYER

The Smart Contract Layer is a crucial component in the multi-level blockchain framework, as it automates the management of supply chain safety and security, while also facilitating efficient processes. They are digital contracts that run by themselves, as their rules are written into code, on decentralized blockchain networks. It eliminates the role of intermediaries, reduces administrative work, and ensures that all parties operate within the agreed-upon rules. Once a shipment arrives, a smart contract can initiate the payment process for the supplier, preventing payments from being delayed or disputed. In supply chain management, smart contracts can automatically handle reordering goods, keep track of stock in real-time, confirm compliance, and oversee product quality. The monitoring and actions regarding temperature and humidity, available through IoT sensors, enable smart contracts to maintain product quality during shipment. Every deal and contract on the platform is logged on the blockchain to ensure transparency and accountability for all parties.

Relying on this layer minimizes mistakes, speeds up transactions and helps build trust among suppliers, manufacturers and customers because there is only one reliable record. Smart contracts also enable supply chain models to automatically adjust in real-time to meet new business or legal demands. Platforms such as IBM Food Trust and Oracle Blockchain demonstrate that utilising smart contracts has reduced the cost of operating in the supply chain, expedited the resolution of disputes, and enhanced the supply chain's efficiency. Ensuring that smart contracts are consistently monitored and periodically audited helps ensure the reliability of the supply chain ecosystem.

3.5. LAYER 4: ANALYTICS AND VISUALIZATION LAYER

By using the Analytics and Visualization Layer, the raw data from blockchain is changed into useful information that helps guide decisions and keep the supply chain improving. By studying transaction histories, sensor values, and smart contracts, this layer gathers information to provide a comprehensive overview of supply chain management. Data analysis tools that use AI and detect unusual changes help in spotting patterns, predicting demands and pointing out risks early.

Real-time maps, performance scorecards and compliance reports are some of the formats visualization dashboards offer. These dashboards enable stakeholders to quickly view key outcomes, including the speed of deliveries, stock levels, and supplier reliability. For instance, logistics managers can monitor all deliveries in real-time, detect bottlenecks, and respond promptly with effective plans. During audits, compliance officers can quickly review immutable records, and procurement teams can analyse how suppliers perform and contribute to sustainability.

Ensuring that data from blockchain can be integrated with legacy BI platforms enables businesses to access insights directly within their day-to-day tasks. The ability to share data and information across departments and companies means everyone involved can understand what is happening with the supply chain. With analytics and visualizations, companies are better able to improve the use of their resources, lower waste and build plans for growth and stability using data. Overall, because of this role, firms can outgrow simply reacting and instead adopt advanced supply chain planning.

3.6. SECURITY AND PRIVACY CONSIDERATIONS

Supply chain management using blockchain relies heavily on ensuring it is secure and private. Guarding data from being changed or tampered with is possible because blockchain is decentralized and immutable, making secure record-keeping possible. At the same time, having multiple stakeholders involved and ensuring fairness between transparency and confidentiality requires special attention at every section of the framework.

Only authorized users are able to access sensitive information in permissioned blockchain applications thanks to Role-Based Access Control (RBAC). Providing access on an individual basis enables the protection of sensitive data while ensuring that necessary disclosures are made in a timely manner. Data is protected while on a computer or when sent over the internet by encryption protocols. Automation offered by smart contracts must always be thoroughly checked and audited to prevent any potential risks posed by malicious users. Checking smart contracts regularly, conducting penetration testing and using verification techniques protect the network by ensuring safe execution of these contracts. When connecting to IoT devices, the system must have robust verification and data validation to prevent forged or altered data from being added to the blockchain.

Using technologies such as zero-knowledge proofs and data anonymization allows us to keep sensitive data secure and still take advantage of the transparency of blockchain. Following data protection laws, such as GDPR, at the international level requires designing rules for how data is stored and accessed. Ensuring security and privacy in all steps of the framework means organizations can develop reliable and trustworthy supply chains that protect both their operations and the interests of stakeholders.

4. IMPLEMENTATION AND CASE STUDY

4.1. IMPLEMENTATION ENVIRONMENT AND TOOLS

For a blockchain supply chain framework to be implemented, the technology stack should be robust, supporting integration, scalability, and security. [16-19] Many developers choose IBM Blockchain, Hyperledger Fabric and Ethereum because they are mature, flexible and supported by many developers. IBM provides tools to help with integration, contract management, and compliance with regulations for businesses, and Hyperledger Fabric provides networks that are well-suited for private transactions. Ethereum is regularly used in decentralized applications because it has smart contract features and is highly open.

The implementation environment typically includes:

- Several key technological components must work together to establish a blockchain-based supply chain system. The basic component of the network is the blockchain platform, with popular platforms including IBM Blockchain, Hyperledger Fabric, and Ethereum. They enable data to be handled expertly and securely throughout the entire supply chain.
- Smart contracts are designed on the blockchain with the proper programming languages to enforce and automate business logic. Developers of systems built on Ethereum use Solidity, as opposed to Chaincode, which Hyperledger Fabric uses. Thanks to smart contracts, parties can agree to and execute contracts without the need for intermediaries.
- Integration middleware is necessary for easy communication between the blockchain and everyday business systems. APIs serve as a means to integrate disparate systems, including ERP platforms, IoT systems, and other legacy technologies, enabling seamless data exchange between platforms.
- IoT devices, such as temperature, humidity, and location sensors, are also part of the process, collecting current data throughout the supply chain. The constant delivery of verified data enhances the company’s ability to comply with regulations and respond promptly to changes.
- Power BI, Tableau, and custom dashboards are used to monitor and inform decisions within the company. With these tools, it’s easy for stakeholders to identify and address trends and issues, ensuring optimal performance.
- Security measures must be robust to safeguard private information and ensure that everyone trusts the platform. Among these, access control for specific roles, protection via encryption, and digital signatures are included to verify the authenticity of data.

The deployment process involves setting up a private blockchain, connecting IoT devices for real-time data capture, and writing smart contracts to automate business operations. APIs facilitate the easy sharing of data with existing systems within the company, while analytics platforms provide valuable insights from blockchain data. Due to this environment, every operation in the supply chain is transparent, traceable, and efficient.

4.2. CASE STUDY: FOOD SUPPLY CHAIN – TE-FOOD

Te-FOOD leads the way in using blockchain in the food supply chain for complete traceability between the farm and your table. IoT devices, QR codes, and blockchain are combined on the platform to track every step in food production, ensuring that all food safety regulations are followed.

TABLE 1 Case Study: Te-food blockchain implementation and impact metrics

Stage	Technology Used	Data Captured	Blockchain Benefit
Farm Production	IoT Sensors, QR	Animal health, feed, origin	Immutable provenance records
Processing	ERP Integration	Processing dates, batch IDs	Tamper-proof documentation
Logistics	GPS, IoT	Location, temperature	Real-time tracking
Retail	QR Code on product	Shelf life, certifications	Consumer transparency
Consumer	Mobile App, QR	Product history access	Trust and engagement

4.3. WORKFLOW DEMONSTRATION

Workflow in the blockchain food supply chain, as portrayed by Te-FOOD, is made up of several computerized and confirmed activities:

- **Data Acquisition**: The sensors at the farm record information on the health of animals, nutrition and the atmosphere. Information is validated and shared securely with the blockchain through Application Programming Interfaces (APIs).
- **Processing & Packaging**: As items are prepared for processing, ERP records the batch details, which are hashed and added to the blockchain. Enforcement of safety rules happens before the next step is allowed.
- **Logistics**: Through IoT, items are monitored for their temperature and current location during transport. If any preset rules are broken, the smart contract alerts the system so the integrity of the product is maintained.
- **Retail & Consumer Access**: Through smartphone technology, the public can trace retail QR codes back to the item's blockchain record. People use the code to see the complete story of how the food was produced and transported.
- **Regulatory & Audit**: Authorities can utilise the blockchain ledger to verify regulations and certificates, facilitating easier audits and investigations.

4.4. OBSERVATIONS AND RESULTS

The use of blockchain technology in food supply chains by companies, including Te-FOOD, has led to greater efficiency, increased transparency, and stronger trust. A major point to emphasize is:

- **Recall Efficiency**: By using blockchain, it became faster to recall products and affected packages were located and removed up to 90% sooner than before.
- **Waste Reduction**: Real-time monitoring and sending alerts reduced losses and waste during transportation and storage processes.
- **Consumer Trust**: Access to the history of each product, via QR codes, made consumers feel more assured and loyal to the brand.
- **Regulatory Compliance**: Data Genesis maintained records by default, making it simpler to understand food safety standards.
- **Operational Efficiency**: User errors and costs associated with information handling were reduced by setting up automatic systems for data capture.

TABLE 2 Te-food blockchain adoption: implementation stages and outcomes

Metric	Before Blockchain	After Blockchain Implementation
Recall Time	3–7 days	< 24 hours
Product Waste	High	Reduced by 30%
Consumer Complaints	Frequent	Significantly decreased
Audit Preparation Time	Weeks	Instantaneous

5. EVALUATION AND DISCUSSION

5.1. PERFORMANCE METRICS

Supply chain managers determine the adoption of blockchain technology by evaluating factors such as traceability speed, data accuracy, stock levels, lead times, and costs. IBM found that approximately 70% of supply chain leaders experienced noticeable improvements in speed, data quality, integrity, and visibility after introducing blockchain technology, rather than relying on manual processes. Inventory levels and lead times increased when companies started using blockchain, but cost reductions emerged only in the months that followed. For example, Walmart's use of blockchain enabled the identification of food origins in seconds, allowing the company to more swiftly address product recalls and maintain food safety.

TABLE 3 Comparative metrics of traditional vs. blockchain-enabled supply chain systems

Metric	Traditional System	Blockchain-Enabled System
Traceability Speed	Days	Seconds
Inventory Lead Time	High	Reduced
Data Integrity	Susceptible	Tamper-proof
Operational Costs	Higher	Lower (long-term)
Recall Time	3–7 days	<24 hours

5.2. TRANSPARENCY AND TRACEABILITY ANALYSIS

Many believe that the most important aspect of blockchain in supply chains is its ability to make everything transparent and traceable. Blockchain ensures that every transaction and piece of data is displayed and valid on a single, inalterable record for all authorized parties. Walmart and AgriDigital, among other companies, have proven that blockchain helps to trace products all the way along the supply chain and thus decrease the risk of counterfeit goods and immediately recall them if needed. Firms such as Pfizer and Merck in the pharmaceutical industry apply blockchain to verify all steps in the production and distribution of drugs, ensuring they are authentic and comply with regulations. By tracking goods instantaneously, companies can make consumers feel more confident and help comply with increasingly stringent international regulations.

5.3. COMPARISON WITH TRADITIONAL SYSTEMS

Paperwork, single-use databases, and manual checks in traditional supply chains result in inefficiency, delays, and increased risk of fraud. Automated capture, validation and sharing of data on a decentralized network through blockchain addresses bottlenecks in the supply chain. The cooperation between Maersk and IBM on blockchain in the maritime logistics sector reduced paperwork, made deliveries more timely, and improved trust among supply chain partners.

TABLE 4 Feature comparison between traditional and blockchain-based supply chain systems

Feature	Traditional System	Blockchain System
Data Sharing	Siloed, manual	Real-time, automated
Auditability	Challenging, delayed	Instant, transparent
Fraud Risk	High	Significantly reduced
Administrative Overhead	High	Lower

5.4. BENEFITS AND TRADE-OFFS

Blockchain adoption improves many aspects of supply chain management. One of the main advantages is that transactions happen with greater openness. The secure and permanent nature of blockchain inspires trust among its users. Because the information is available, every person in the supply chain can verify that the information is accurate and genuine. Additionally, traceability improves significantly with blockchain. Using blockchain enables the real-time verification and tracking of products, thereby making it easier to identify fakes and expedite product recalls. Accountability and compliance improve thanks to the detailed tracking of data, especially for sectors that face tough rules.

Automation greatly improves the efficiency of work. Blockchain simplifies workflows by enabling the automation of manual tasks and facilitating the completion of transactions quickly. Because of this, organizations can reduce their paperwork expenses and work more efficiently. Additionally, the security features of blockchain technology ensure data safety and reliability, while also preventing unauthorised changes. Nevertheless, several factors must be considered before implementing AI in supply chain management. Implementing these technologies is often very expensive. Connecting blockchain to the existing IT systems that SMEs already rely on can be both pricey and complicated, which makes it challenging for SMEs to adopt this technology. Public chains also have to worry about scalability, as their transaction speeds can slow down when there is a high level of activity on the network. Still, even though blockchain technology is secure, human mistakes can create weaknesses. Inaccurate data manually input at the start of the process may still weaken the integrity of the database.

5.5. LIMITATIONS AND ASSUMPTIONS

Several factors limit the use of blockchain in supply chain management. Failures in data entry by humans at the edges can pollute the data, stressing the point that strong validation approaches are necessary. Issues such as setting up access permissions and overseeing networks involving multiple parties remain challenging to resolve. Scalability remains an issue, particularly for public blockchains, which can become clogged when a large number of transactions occur. Transparency and knowing where goods come from are especially important for many consumers in actualizing luxury foods and products, which helps the business case for blockchain in these areas.

5.6. ASSUMPTIONS

All participants in the system are ready to use the blockchain, and that data can be collected from IoT devices in real-time. It further requires that regulatory regimes be favorable to digital ledger technologies.

6. FUTURE WORK

Future blockchain work in supply chain management will aim to enhance how systems can collaborate, scale up processes, and incorporate new technologies. Standard cross-chain protocols have been considered, supporting data transfers between numerous blockchains and traditional financial systems. As a result, organizations will find it easier to collaborate in global supply chains, lowering division and raising how clear and traceable everything is. Additionally, linking advanced IoT devices and AI enables predictive supply chain management, real-time risk evaluation, and automatic decision-making, thereby significantly enhancing both efficiency and resilience in operations.

Another focus is to explore technologies such as zero-knowledge proofs and confidential computing, as they enable companies in highly regulated industries to maintain data confidentiality while still maintaining sufficient transparency. Future efforts will also consider the economic factors that hinder adoption, along with the establishment of affordable ways for SMEs to join these platforms and the development of standard, multi-stakeholder governance models. As regulations continue to evolve, ongoing research is necessary to ensure compliance with global standards in blockchain-based supply chain systems. The merging of blockchain with IoT, AI and advanced analytics will open the door for robotic supply chain ecosystems that manage themselves.

7. CONCLUSION

All in all, the use of blockchain technology in supply chain management makes it possible to achieve greater transparency, traceability, and accomplish tasks more efficiently. The suggested framework involves data acquisition, blockchain use, signing deals with smart contracts and advanced analytics, which illustrates how decentralized ledgers can tackle common issues of online data isolation, fraud and delays in recalling goods. Real-life cases from the food and pharmaceutical industries reveal that blockchain increases the speed of recalls, reduces waste, fosters more reliable compliance with regulations, and helps increase consumer trust. Implementing blockchain in the supply chain yields several positive outcomes, although businesses must manage the issues of implementation cost, scalability, and data management. Progress in cross-chain interoperability, privacy protection and AI analytics will be vital to overcome the existing issues. As technology advances and regulations change, blockchain is poised to become a key element in robust, intelligent, and environmentally friendly supply chain systems. When organizations support this movement, they can build supply chains that are more honest, protected and flexible, bringing more benefits to everyone.

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