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Original Article

Blockchain Technology in Supply Chain and Logistics: A Comprehensive Review of Applications, Challenges, and Innovations

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Abstract - The difficulty in managing and controlling supply networks is exacerbated by their globalization. Blockchain, a decentralized digital ledger technology, has the power to improve global supply chain management by making it more transparent, traceable, and secure. This paper explores the amazing potential of blockchain technology in logistics and supply chain management (SCM), particularly in regards to its capacity to enhance trust, transparency, and traceability. Blockchain offers a distributed and immutable record that guarantees safe transactions and real-time monitoring, in contrast to conventional supply chains that encounter problems including data sharing, fraud, and a lack of responsibility. The paper discusses the integration of blockchain with key supply chain entities, including registrars, certifiers, and standards organizations, and highlights its role in automating processes through smart contracts and IoT integration. Despite its promising benefits, the paper identifies several challenges, including system integration, scalability, data privacy, and regulatory uncertainties, and suggests future research directions to overcome these barriers. The study aims to advance the understanding of blockchain applications in SCM and provide insights for developing efficient, resilient supply chain networks.

Keywords - Blockchain Technology, Logistics, Supply Chain, Transparency, Accountability, Smart Contracts, Blockchain Integration.

1. Introduction

There have been massive shifts in modern supply chains, with an operational role now serving as an autonomous SCM function. In order to meet customer needs, supply chain processes involve a wide range of logistical duties, including organizing, carrying out, and managing the effective movement and storage of goods, services, and associated data from their point of origin to their location of consumption[1]. By integrating and streamlining these procedures, you may get an advantage in supply chain velocity, inventory turnover, revenue optimization, transparency, and efficient customer service delivery [2].

A complexity of supply chains has grown owing to an interaction of several geographically scattered companies that operate autonomously and often compete to serve their clients, making it difficult to accomplish these goals [3][4]. There are a lot of unknowns and dangers in supply chains, on top of all the complexity[5]. For example, trade partners may engage in opportunistic behaviour (e.g., cheating or distorting information) [6], there is a chance of privacy leaks, fraud or cybercrime may happen, and it could be difficult to identify fake products.

In an effort to address these issues, managers at major organizations in a broad range of industries are attempting to digitize SCM [7]. The term "digitization of supply chains" describes how businesses are using inter-organizational technologies to communicate and conduct business with their trading partners (such as important suppliers and consumers) throughout the supply chain. As a whole, the SCM industry is expected to achieve $19 billion in sales by 2021 as a result of technological advancements [8]. Improved agility, responsiveness, and security in digitalized supply chain networks are just a few ways in which businesses reap the benefits of digitization [9].

Businesses may decrease costs and increase efficiency by digitizing supply chain operations, which allows them to better satisfy consumer needs for personalized goods. To keep operations running and supply chain management at a high level, businesses have

started using blockchain technology[10]. Blockchain can be defined as a *"Digital distributed ledger that records transactions in chronological sequence with the goal of creating permanent and unchangeable records"* [11]. A cryptographically secured hash function connects a series of time-stamped blocks in the distributed ledger [12].

1.1. Motivation and Significance of the Paper

The focus of this research is on the profound potential of blockchain technology to revolutionize logistics and supply chain practices. Traditional supply chain systems deal with various challenges which include transparency problems together with data sharing issues and opportunities for fraud along with potential errors. Blockchain technology solves supply chain issues by maintaining immutable records within secure decentralized structures which improves tracking capabilities and enhances organization reliability and process speed. The increasing focus on responsible supply chains necessitates robust verification systems which will determine product authenticity as well as compliance with standards. This research studies blockchain applications while addressing domain-specific challenges and innovation to help advance future research-based supply chain implementation strategies for creating efficient resilient networks. This research mostly adds to the following areas:

- The article delves at the ways in which smart contracts on the blockchain might revolutionize SCM by fostering trust, transparency, and traceability.
- It introduces key entities such as registrars, certifiers, and standards organizations that are crucial for blockchain-based supply chains.
- Blockchain enables detailed tracking of product attributes (nature, quality, quantity, location, ownership), enhancing transparency without a central authority.
- The paper highlights blockchain's role in improving logistics through IoT integration, real-time tracking, and automation of documentation.
- It identifies challenges like system integration, scalability, and data privacy, while suggesting future research directions to enhance blockchain adoption in supply chains.

1.2. Structure of the Paper

This paper examines blockchain technology in SCM and logistics. Section I introduces its benefits in traceability and transparency. Section II explores its role in improving logistics efficiency. Section III discusses challenges like integration and data privacy. Section IV highlights innovative applications in SCM. Section V reviews literature on blockchain in logistics. The paper concludes with research gaps and future directions.

2. Blockchain-Based Supply Chain

Blockchains have the ability to revolutionize supply chain management in many ways, including design, organization, operations, and more. Supply chain management is due for a radical overhaul thanks to blockchain technology, which ensures data is trustworthy, verifiable, and genuine, and which, in conjunction with smart contracts for a thrustless environment, promises to revolutionize the industry. This section will examine the advantages of blockchain technology, its operation, and potential new features for SCM, with an emphasis on the manufacturing and commodities supply chains.

The increasing usage of blockchain technology in supply chains has led to new applications that are unrelated to Bitcoin. Privileged permit-based blockchain networks better suit supply chain systems rather than the typically open public types of blockchain. The determination of privacy levels stands as an essential initial step because permissioned blockchain networks can be open to public participation. An example of a conventional supply chain making the switch to a blockchain-based one is seen in Figure 1.

In contrast to conventional supply chains, blockchain-based ones include four main players. Registrars are responsible for assigning distinct identities to participants in the network. Regulatory and technical committees that set standards, like Fairtrade for ecologically responsible supply chains or blockchain technology [13]. Those involved in the certification process who provide credentials to those who take part in supply chain networks. For the sake of maintaining trust in the system, it is necessary to certify producers, merchants, and customers via a recognized auditor or certifier.

The movement of products and resources along the supply chain is thus affected. The idea is that all relevant stakeholders should be able to quickly access product profiles through a digital blockchain presence for each product. To ensure that only approved individuals are able to use a product, security measures are put in place. Product status, product kind, and proposed product standards are just a few examples of the many types of information that may be gathered [14]. Products' information tags serve as identifiers that connect their physical items to their digital counterparts on the blockchain [15].

The five most important aspects of a product that blockchain technology can bring to light and describe are: its nature, its quality, its quantity, its location, and its ownership. Customers can observe the continuous chain of custody and transactions from the purchase of raw materials all the way through to the sale since the blockchain eliminates the requirement for a reliable central organization to run and maintain the system. A verifiable ledger records any change that corresponds to a transaction on any of the many information dimensions that make up blockchain.

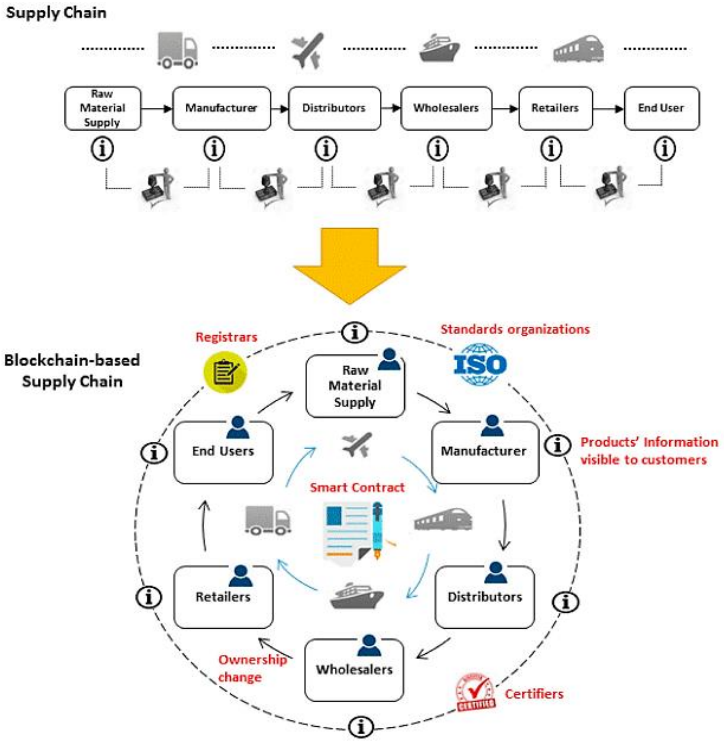

Figure 1. Supply Chain Transformation

To satisfy the needs of automated governance, blockchain technology is being developed to simplify the movement of data and products along the supply chain by virtue of its immutability and reliability. The industrial, durable, commodity, goods economy may give way to a more information-based, customized economy as a consequence of this change. The qualities of the materials used in production will be less important than information, communication, and knowledge [16]. As an example, consumers may keep tabs on product details, which would boost their confidence in the product's attributes [14].

3. Perspective of Blockchain Technology & Supply Chain in Logistics

The term "supply chain" describes the interconnected web of companies that work together to create the products and services that consumers buy [39].

The logistics 4.0 framework enables organizations to seamlessly link internal operational processes which simplifies material throughput control from start to finish. Smart transport systems including trucks, cargo space, and pallets support modern monitoring methods while IoT sensors and network interfaces let us track crucial logistics data about temperature and perpendicular orientation and illumination conditions in real time[17]. Modern technologies create complete visibility of freight distribution from the beginning of the supply chain to the end.

The complete realization of Logical 4.0 and Industry 4.0 requires an essential dependence on big data utilization. Big data spans the massive amounts of both structured and unstructured data that generates rapidly while offering analysis opportunities through advanced analytics with warehousing capabilities. Advanced analytics produce precise timely information which helps organizations make better decisions. Blockchain technology through its big data infrastructure enables secure transaction tracking for money alongside data and information[18]. Through Blockchain implementation supply chains remove delays as well as decrease costs and human mistakes by documenting entire product exchanges which result in permanent documentation from manufacturing through sales.

Many people believe that blockchain technology might work well in the logistics and SCM industries. As a product moves from manufacture to consumption, its history can be preserved by recording the data generated at each step as a transaction [19]. Blockchain technology has several potential advantages, one of which is the capacity to: (i) keep track of everything that moves through the supply chain, from items and containers to their movements; (ii) record everything (receipts, orders, invoices, and payments included); and (iii) uniformly record all digital assets alongside physical ones, including certificates, warranties, copyrights, licenses, serial numbers, and bar codes.

Blockchain technology has the potential to greatly enhance logistics and supply chain operations. The supply chain stands to gain a lot from even the most basic use of blockchain technology. The primary data pertinent to supply chain management may be identified by recording product transfers on the digital ledger as transactions[20].

4. Challenges of Blockchain Applications in Logistics

Decentralized techniques for monitoring products and transport containers may be used by businesses in the manufacturing and logistics sectors. Extensive technological solutions are necessary to meet the growing need for supply chain transparency, which enables full traceability [21]. This is a common problem with IT solutions that prioritize centralized systems with intricate permission structures [22]. Due to their prior work on these problems, blockchain technology or related ideas may provide a solution. Below are the discussed key challenges and visualization of IBM blockchain supply chain in Figure 2:

- Integration with Existing Systems: A blockchain implementation requires complex and expensive integration work with existing legacy systems[23]. The intricate access rights used in centralized information technology solutions create difficulties when trying to adapt them to decentralized computing frameworks.
- Scalability Issues: Buildings based on blockchain network often experience reduced performance when processing the vast transaction volume occurring in logistics and involving Internet of Things devices thereby increasing operational costs and extending processing durations[24].
- Interoperability: Overcoming the challenge of making blockchain platforms work together with existing technologies including RFID automation and supply chain management tools demonstrates an important limitation[23].
- High Initial Costs: Blockchains require extensive resources when developers deploy solutions together with supporting infrastructure while leading small to medium businesses away from this tech[25].
- Data Privacy and Security: Blockchain systems deliver transparency in supply chain management yet overall data protection and unauthorized access prevention remains a priority especially in protective supply chain operations.
- Regulatory and Legal Uncertainty: The absence of uniform regulatory frameworks for blockchain technology generates procedural confusion which reduces its widespread implementation across global supply logistics operations.
- Energy Consumption: Blockchain networks which operate using proof-of-work consistent mechanisms result in substantial energy usage which causes sustainability concerns[26].
- Complexity of Smart Contracts: A deployment of error-free advanced smart contracts guiding logistics processes depends heavily on specialists who are scarce in the market.
- Adoption Resistance: Many supply chain stakeholders show reluctance to embrace blockchain adoption because it lack knowledge about the technology and fear new approaches and regard decentralization as risky.

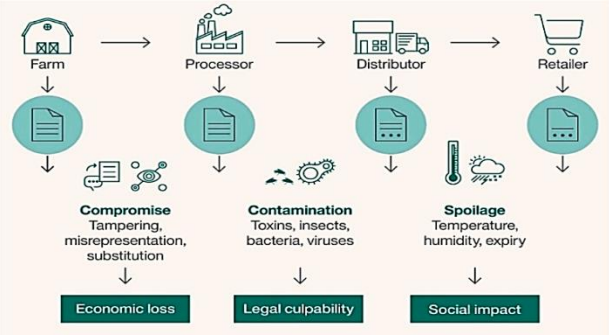

Figure 2. IBM Blockchain Supply Chain

5. Blockchain Innovation in SCM and Logistics Industry

Blockchain innovation itself has been subject to much investigation; nevertheless, the intersection among blockchain innovation and SCM logistics. There are organisations who claim to have launched pilot operations of using Blockchain in SCM administration [27]. However, there is a lack of detailed information on the specific use of these projects, and the shown pilot initiatives are

blockchain-based [28]. The retail sector also anticipates benefits from this innovation in the form of improved traceability. An continuing study on the usage of 'Bitcoin data structures' in supply chain administration states that the final guarantee of the usefulness of the information administration approaches shown is based on observation. Furthermore, the experts state that while certain Bitcoin execution aspects would be useful in an SCM context, there are currently very few implementations that support this. It is challenging for industry performers to envision how the technology may be used to their unique company situation because to a lack of study on the subject. The performing artists in the industry would benefit from an evaluation demonstration to better understand the innovation and maybe develop new executions, but there isn't one. The goal of this study is to determine which systematic review sources should be used to evaluate if blockchain innovation is suitable for SCM and logistics.

5.1. Blockchain Innovation within Business Engagements

Almost every business interaction nowadays involves blockchain technology. Throughout its most formative years, it served primarily as an insider's tip, with the identity of at least one baffling figure staying unknown. Not everyone knew this at the time, but in September 2015, nine financial institutions including JPMorgan Chase, Goldman Sachs, Barclays, and others came together to build a new Blockchain-based system for financial services. Then, with new firms and corporate projects popping up almost every day, Blockchain had become the talk of the town in the financial technology industry. The logistics and SCM administration were slower to grasp the significance of Blockchain technology and its possible effects on their industry. Blockchain's ability to make information plain for all users of the system, providing a single goal of truth, is one of its notable guarantees. Logistics and SCM have a significant and difficult task in enhancing the visibility of the manufacturing network. Nobody should be surprised that certain logistics experts see Blockchain as having "colossal potential," being a "truly necessary stage for monetary restoration," and having the power to " reshape the manufacturing network and disrupt their product delivery, advertising, purchasing, and consumption practices." When all the pieces are in place, Blockchain may be the "holy chalice" of digital currency.

5.2. Blockchain within Stages of Business Engagements

However, as is often the case with emerging innovation, innovation providers, experts, and authors seem to be the main forces behind the attention surrounding Blockchain. Medium-sized company logistics managers claim to know very little about blockchain [29]. This is due to the fact that Blockchain is still in its infancy and there aren't many convincing use cases that demonstrate its advantages over existing IT systems [30]. Blockchain research in SCM and logistics is in its infancy and should look at potential uses such as these:

- Business show improvement: Companies need to establish policies and strategies that foster growth and sustainability in order to reap the mixed advantages of digitalization and inventory networks in their operations.
- Information demonstrates stages: Data in supply chains should be collected, stored, and communicated using appropriate data models. This often calls for stage enhancement and stage-to-stage connecting.
- Business process models for store network availability: The availability and standards of business processes can only be improved with new knowledge and ways of doing things. This relates to the ways in which business process exchanges may be carefully linked to interacting partners in the store network.
- Operator administrations for information exchange between performing artists: Intermediaries in the integration channel are tasked with coordinating and exchanging data across several artists and frameworks.

Blockchain technology gives businesses the option to digitalize internal administration expenses and increase productivity or digitalise external systems to manage intensity, so reducing internal administration costs and increasing productivity. In a nutshell, blockchain innovation from a contemporary standpoint means that the company controls exchange costs by figuring out inner administration charges for handling marketplace exchange costs.

6. Literature Review

Table I provides a concise overview of a literature review on blockchain technology as it pertains to SCM and logistics. Li and Huang (2019) suggested a blockchain-powered workflow management system (BCWMS) for facilitating the central sharing of diverse logistical resources among different customers. The BCWMS is empowered by three crucial breakthrough technologies. The first is a tech-enabled gateway that allows for the control of diverse logistical resources using UPnP (Universal Plug and Play). Secondly, a workflow operating platform is tailored to various business logics in order to efficiently and effectively coordinate logistical resources. The combination of blockchain and agent technologies in the architecture of a resource blockchain ensures data dependability, allowing various clients to make better decisions based on reliable front-line resource execution data[31].

Li et al. (2018) further develops, using the traditional network maximum flow algorithm as a foundation, a model for assessing charitable contributions of material goods in service of social welfare. Their four months of data collection and analysis led them to the following conclusions: blockchain technology has the potential to enhance society by boosting user confidence in the project,

enhancing the cleanliness coefficient of the system, and raising the quality of donations for humanitarian causes. It is the paper's contention that this blockchain platform offers a technological means of increasing societal well-being. Highlighting the common ground between the public welfare sector, which demands absolute honesty and trustworthiness, and the logistics sector, which has a plethora of established blockchain application [32].

Fu and Zhu (2019) has given rise to ideas for blockchain-based intelligent logistics system application research, and it both positively references and guides the development of blockchain application research. "Traceability" is the defining feature of blockchain technology. The methods of data storage and access, consensus authentication, and algorithm model construction are all presented here. Improving the decision-making process in terms of science, logic, and intelligence is achieved via the introduction and analysis of relevant large data from intelligent logistics systems [33].

Treiblmaier (2018) study aims to fill the current knowledge gap about the potential blockchain implications for SCM by presenting a framework based on 4 well-established economic theories: PAT, TCA, RBV, and network theory. Theoretical and industry-relevant research issues may be derived from these theories. This is a framework for intermediate-range theory along with a number of research topics in an effort to start and encourage an academic conversation on the possible effects of the blockchain[11].

Amr et al. (2019) presents three possible uses of Blockchain technology to address these issues. Here, blockchain technology aims to solve two major problems with the supply chain: sharing resources and making data more transparent. The company's objectives and goals take these concerns into account. An increasingly important part of their life has been shaped by technology. To create commodities or provide services, technology encompasses " all the information, goods, procedures, instruments, techniques, and frameworks"[34].

Parung (2019) investigates blockchain's possible advantages for environmentally friendly SCM. Environmental, societal, and economic factors all work in favour. It goes on to detail the benefits of blockchain technology in reducing transportation and other environmentally harmful resource use. Cost and time efficiency may improve using this technology. As organizations' reputations improve, blockchain technology may benefit them socially. This study also provides three blockchain implementations in three sectors. This paper also notes that adopting this technology for supply chains may harm sustainability[35].

Table 1. Presents the Summary Based On Blockchain Technology in Supply Chain and Logistics

References	Key Concepts	Technologies/Approaches	Results/Findings	Challenges	Future Directions
[31]	Blockchain-enabled workflow management, heterogeneous logistics resources	Gateway technology, UPnP management, Workflow operating platform, Resource blockchain	Improved coordination of logistics resources, data reliability for decision-making	Integration of heterogeneous resources, scalability	Further development of blockchain-enabled logistics systems for various industries
[32]	Blockchain in philanthropy and social welfare	Blockchain platform, Network maximum flow algorithm	Increased trust in charitable projects, enhanced material quality, improved public welfare	Data privacy, platform scalability	Exploring blockchain's potential in other welfare sectors
[33]	Intelligent logistics system based on blockchain	Blockchain, Consensus authentication, Data storage and access mechanism	Improved decision-making, better system rationality, and intelligence	Data integration, consensus mechanism efficiency	Refining decision-making algorithms and integrating more data sources
[11]	Blockchain's impact on supply chain management (SCM)	Principal agent theory (PAT), Transaction cost analysis (TCA), Resource-based view (RBV), Network theory (NT)	Framework for studying blockchain's implications in SCM, academic discussion initiation	Lack of theory-based research questions, industry relevance	Further exploration of blockchain's role in SCM through established economic theories

[34]	Blockchain's role in data transparency and resource sharing in supply chains	Blockchain technology	Enhanced data transparency and resource sharing in supply chain strategies	Integration with existing systems, organizational resistance	Developing use cases and real-world applications of blockchain in supply chains
[35]	Blockchain for sustainable supply chain management	Blockchain technology	Environmental, economic, and social benefits, improved cost and time efficiency	Potential negative impacts on sustainability, environmental concerns	Investigating blockchain's long-term sustainability impact and environmental footprint

7. Conclusion and Future Work

Logistics and SCM professionals have taken notice of the new blockchain technology. This article highlights how blockchain technology can revolutionize SCM by offering a safe, transparent, and decentralized framework. The ability of blockchain to improve traceability, reduce fraud, and ensure data integrity can significantly enhance supply chain efficiency and trust among stakeholders. However, while blockchain offers considerable advantages, challenges such as system integration, scalability, regulatory compliance, and energy consumption must be addressed for its broader adoption. Overcoming these barriers will be crucial for realizing its full potential in the supply chain industry.

The present constraints of current systems should motivate future research towards the development of energy-efficient and scalable blockchain solutions. Making blockchain work better with other emerging technologies like the IoT and AI might open up new possibilities for optimizing the supply chain. Privacy concerns should also be prioritized by exploring advanced encryption techniques and permissioned blockchain models. Further empirical studies and case implementations will help assess the real-world impact and long-term sustainability of blockchain in SCM.

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