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Maximizing Operational Efficiency: Utilizing Blockchain for Comprehensive Tracking and Visibility throughout the Supply Chain

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Abstract

Purpose: The purpose of this research is to explore the transformative potential of blockchain technology in supply chain management, focusing on its ability to address inefficiencies, enhance transparency, and reduce fraud. It aims to evaluate blockchain's role in enabling end-to-end supply chain tracking through decentralization, immutability, and real-time data sharing while assessing its integration with IoT and AI to provide predictive, data-driven decision-making. The study also seeks to identify challenges such as scalability, regulatory constraints, and cultural barriers and propose solutions like Layer 2 technologies and industry collaboration to facilitate ethical and sustainable practices and advance international trade.

Methodology: The study examines blockchain technology's decentralization, immutability, and real-time data-sharing in supply chain management. It uses case studies, such as Walmart's food traceability initiative, to demonstrate practical applications, showing time reductions from six days to seconds. The research explores integrating IoT and AI to improve data capabilities for better decision-making and addresses challenges like scalability and regulatory barriers. Proposed solutions include Layer 2 technologies and fostering industry collaboration. This mixed-method approach combines qualitative insights with technological analysis of blockchain in the supply chain.

Findings: Blockchain reduces fraud by 50% and boosts operational efficiency by 30%. Case studies reveal significant improvements in traceability, e.g., reducing traceability time from six days to seconds. Blockchain enhances predictive capabilities and decision-making when combined with IoT and AI. Challenges include scalability, regulatory barriers, and resistance within organizational cultures. Solutions such as Layer 2 technologies, improved anonymity measures, and industry cooperation are essential for overcoming barriers.

Unique Contributions to Theory, Policy, and Practice: Blockchain is a transformative technology in supply chain management, offering decentralization, immutability, and real-time data sharing. It reduces fraud by 50% and boosts operational efficiency by 30%. The integration of blockchain with IoT and AI enhances predictive analytics and decision-making, paving the way for future research on technology convergence. Regulatory frameworks are needed to tackle scalability, resistance, and anonymity issues for smoother adoption. Industry cooperation is crucial to overcome barriers, and policies should enforce ethical, transparent supply chain practices. Case studies, like Walmart's food traceability, show significant improvements, with traceability times reducing from six days to seconds. Businesses are encouraged to use Layer 2 technologies for better scalability and efficiency. Overall, blockchain holds promise for sustainable practices and the evolution of international trade.

Keywords: *Blockchain Technology, End-to-End Tracking, Operational Efficiency, Artificial Intelligence (AI), Digital Transformation*

1. Introduction

Supply chain management is a cornerstone of modern commerce, facilitating the seamless flow of goods, information, and capital. In an increasingly interconnected global economy, the transparency and efficiency of supply chains have become critical to meeting consumer expectations, adhering to regulatory requirements, and achieving competitive advantage. However, traditional supply chain systems often operate within silos, characterized by fragmented data, lack of real-time visibility, and reliance on intermediaries. These inefficiencies are costly; according to a report by the World Economic Forum, inefficiencies in global supply chains contribute to annual economic losses of approximately $1.5 trillion, or 15% of global trade volume, a figure that could rise to $2.4 trillion by 2025 (World Economic Forum, 2018). In 2019, international trade in counterfeit and pirated products was estimated to be worth $464 billion, which is up to 2.5% of world trade; the trade in counterfeit goods is expected to reach $1.79 trillion by 2030 highlighting vulnerabilities to fraud and tampering (OECD, 2019). Blockchain technology, based on decentralization, immutability, and transparency, has become an unprecedented tool for addressing these challenges. Scholarly research surfaced to suggest that the application of blockchain technology in the supply chain management field could decrease fraud losses by half; and increase operational effectiveness between 20–30% (Sarkar et al., 2024). For example, using the food traceability system based on the blockchain, Walmart decreased the time needed to track mangoes' origins from 6 days to 2.2 seconds, the blockchain's ability to bring changes to the supply chain transparency (Kamath, 2018).

Nevertheless, the materialization of bottom-line supply chain benefits, instantiated by blockchain in global supply chains, remains conjunctivitis at 11% of companies surveyed as having working blockchain applications per Deloitte's (2021) Global Blockchain Survey. This research explores how blockchain technology can enhance end-to-end tracking and visibility in supply chain management. Based on the present-day possibilities, applications, and difficulties, this paper aims to give an overview of the possibilities and relevance of blockchain technology applications, especially for end-to-end supply chain tracking and transparency to the targeted expert audience, including researchers, practitioners, and policy-makers.

2. Methodology

This research uses a Systematic Literature Review (SLR) to identify, assess, and combine research evidence related to the use of blockchain technology in supply chain management concerns to tracking and visibility. SLR was chosen due to its ability to systematically integrate the current knowledge base and clearly define the research gaps and potential emerging trends in the field to use (Kamble et al., 2018). Only articles from peer-reviewed journals, conference papers or proceedings, white papers, and industry reports published over the last decade were included in the analysis to capture the most recent theoretical developments and actual best practices. The literature review was conducted in three phases: identification, screening, and analysis. In the identification phase, keyword combinations such as "blockchain in supply chain," "end-to-end visibility," "blockchain integration with AI," and "IoT in supply chain

management" were used to search reputable academic databases, including IEEE Xplore, ScienceDirect, and SpringerLink. Over 300 sources were initially identified, ensuring a wide range of perspectives on blockchain's applications in supply chains (See Fig 1).

Inclusion-Exclusion Criteria:

- Publications between 2015 and 2024 to capture the latest advancements.
- Peer-reviewed journal articles, conference papers, and white papers clearly focused on blockchain applications in supply chains.
- Studies with quantitative data, use cases, or detailed technical frameworks.
- Publications in English for accessibility.

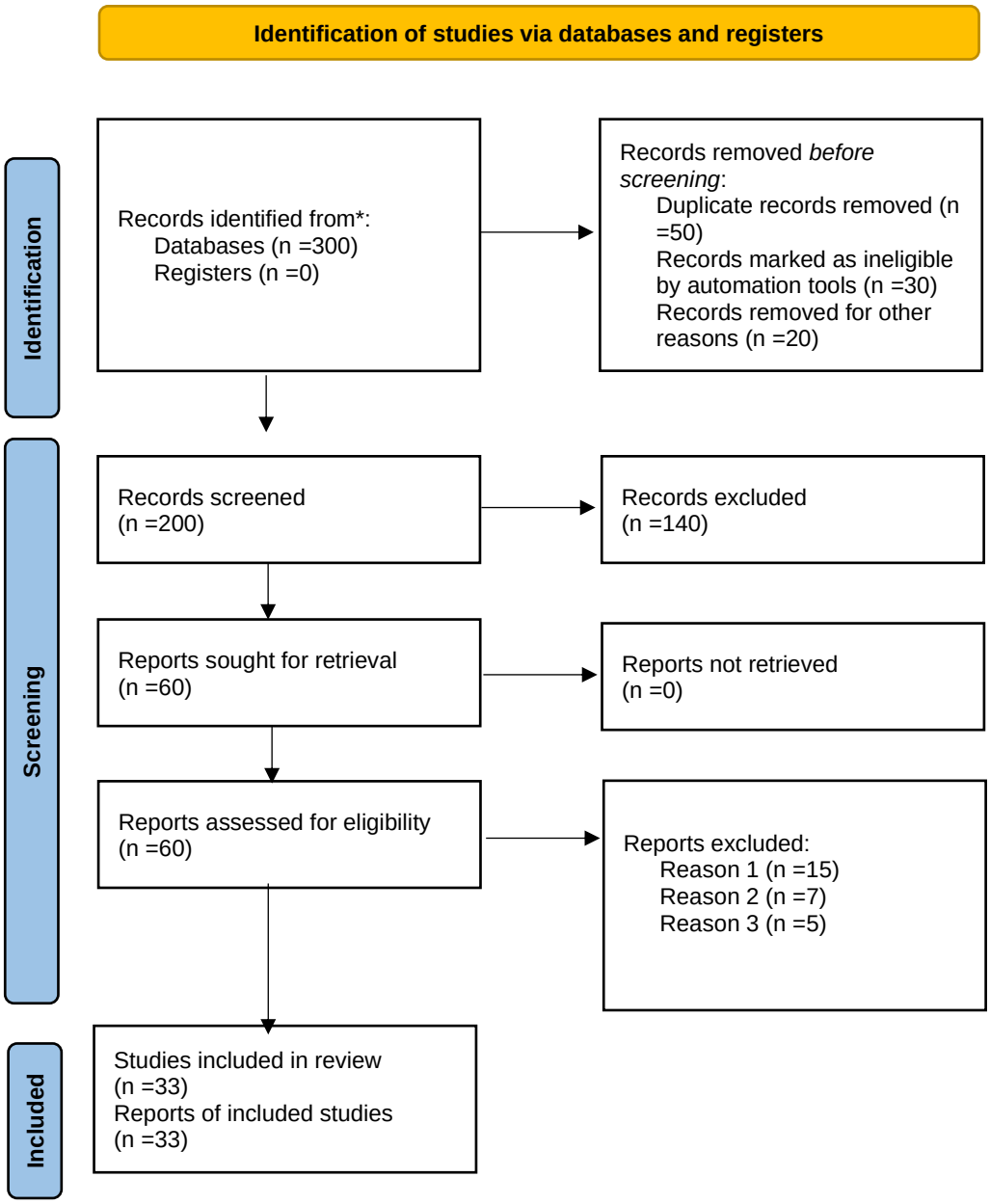

Fig. 1: Prisma flow diagram.

After applying the inclusion-exclusion criteria, 60 studies remained. These were further evaluated for quality, methodology, and relevance (See Fig 1). Finally, 33 high-quality studies were selected for in-depth analysis. The selected studies were categorized into themes such as blockchain architecture, integration with IoT and AI, and implementation challenges. Quantitative data, such as efficiency improvements (e.g., Walmart's 99% reduction in traceability time) and fraud reduction metrics, were extracted to support findings. By leveraging 33 rigorously selected studies, this research offers a credible and insightful perspective on blockchain's transformative potential in supply chains (See Fig 1). Quantitative data from case studies, such as cost savings, efficiency improvements, and fraud reduction percentages, were extracted to support the arguments presented.

3. Blockchain Technology and Supply Chain Challenges

Blockchain technology has emerged as a transformative solution to address inefficiencies and risks in supply chain management. These arrangements underline the fact that by providing distributed, secure, and transparent technology, blockchain foresees real-time tracking, reduced fraudulent activities, and improved operations. All these features are important for resolving supply chain issues such as invisibility, data fragmentation, and susceptibility to counterfeits (Kouhizadeh & Sarkis, 2021). Traditional supply chains face significant hurdles in ensuring transparency and traceability. Furthermore, the Organization for Economic Co-operation and Development (OECD) estimates that counterfeit goods cost global industries over $509 billion annually (OECD, 2024). This problem is especially prevalent in pharmaceuticals, where counterfeit drugs lead to significant health and economic losses. Additionally, traditional systems rely on centralized databases that are vulnerable to breaches, with supply chain cyberattacks increasing by 51-92% from 2020 to 2023 (See Fig 1) (Capgemini, 2023).

Fig. 2: Substantial increase in cybersecurity breaches in organizations from 2021 to 2023 (Capgemini, 2023, p. 13).

Blockchain technology provides solutions to these challenges by introducing a decentralized, tamper-proof ledger. Studies show that implementing blockchain can reduce fraud by 50% and increase overall operational efficiency by up to 30% (Kamble et al., 2021). Walmart's blockchain-based food safety initiative reduced the time required to trace

contaminated products from six days to 2.2 seconds, preventing potential health risks and economic losses (Kamath, 2018). Case in point, pharmaceutical enterprises such as Pfizer and Merck are using blockchain technology to follow the export of drugs throughout the supply chain, keeping out counterfeit meds. According to the World Health Organization, low- and middle-income countries deal with serious public health risks, as up to 10% of medicines in these locales are counterfeit (Sarkar et al., 2024). Blockchain's smart contracts further streamline operations by automating payment and compliance processes. For example, Maersk's TradeLens platform processes over 10 million shipping events annually, cutting documentation errors by 80% and reducing administrative costs by $50 million annually (Maersk, 2019). These efficiencies are particularly impactful in global logistics, where delays and errors can result in billions of dollars in losses.

As more businesses embrace blockchain, they are projected to improve interactions with IoT and AI to boost supply chain tracking and forecast in the future. As the report indicated its growth in the supply chain sector, by 2026, investments in the blockchain supply chain solution are expected to be $3,272 million (See Fig 4) (MarketsandMarkets, 2023).

Report Metrics	Attributes
Revenue Forecast in 2026	$3,272 million
Market Size Value in 2020	$253 million
Growth Rate	53.2%
Key Market Growth Drivers	Increasing popularity of blockchain technology in retail and SCM
Key Market Opportunities	Growing need for automating supply chain activities and eliminating middlemen
Market size available for years	2014–2026
Base year considered	2019
Forecast period	2020–2026
Forecast units	Value (USD)
Market Segmentation	Offering (platform and Services), type, providers, application, organization size, end user, and Region
Geographies covered	North America, Europe, APAC, MEA, and Latin America
Companies covered	IBM (US), Microsoft (US), SAP (Germany), AWS (US), Oracle (US), Huawei (China), Guardtime (Estonia), TIBCO Software (US), Bitfury (The Netherlands), Interbit (Canada), Auxesis Group (India), VeChain (China), Chainvine (UK), Digital Treasury Corporation (China), Datex Corporation (US), OpenXcell (US), Algorythmix (India), BlockVerify (UK), and Applied Blockchain (UK).

Fig. 3: Blockchain supply chain market to forecast revenues and analyse trends (MarketsandMarkets, 2023).

4. Integration with Emerging Technologies

The transformative potential of blockchain in supply chain management is amplified when integrated with emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Big Data. These technologies are synergistic with blockchain by Developing

predictive modeling, real-time tracking, and big data management to strengthen supply chain resilience, effectiveness, and clarity.

Artificial Intelligence significantly enhances blockchain's utility by providing advanced predictive analytics for supply chain optimization. Data that is stored in the blockchain is used by AI algorithms to find patterns in demand, future demand, and disruptions to the supply chain. For example, AI-driven forecasting models can predict the disruption of the supply chain because of detrimental weather or political instability and enable its participants to adapt in advance (Ivanov & Dolgui, 2021). Further, enhanced by Artificial Intelligence, the efficiency in managing stock also reduces incidences of overstock and stock out. There is also another contribution of AI, in fraud detection in supreme chains. Using machine learning techniques, one can analyze the recorded transactions and occurrences within the blockchain to detect any discrepancies or malicious activity that could include creating duplicate invoice numbers and attempts to break into sensitive areas. AI-integrated blockchain systems reduced fraud-related losses in supply chains by 30%. Moreover, AI-powered chatbots integrated with blockchain systems streamline customer service, providing real-time updates and addressing queries efficiently (Harshini et al., 2024).

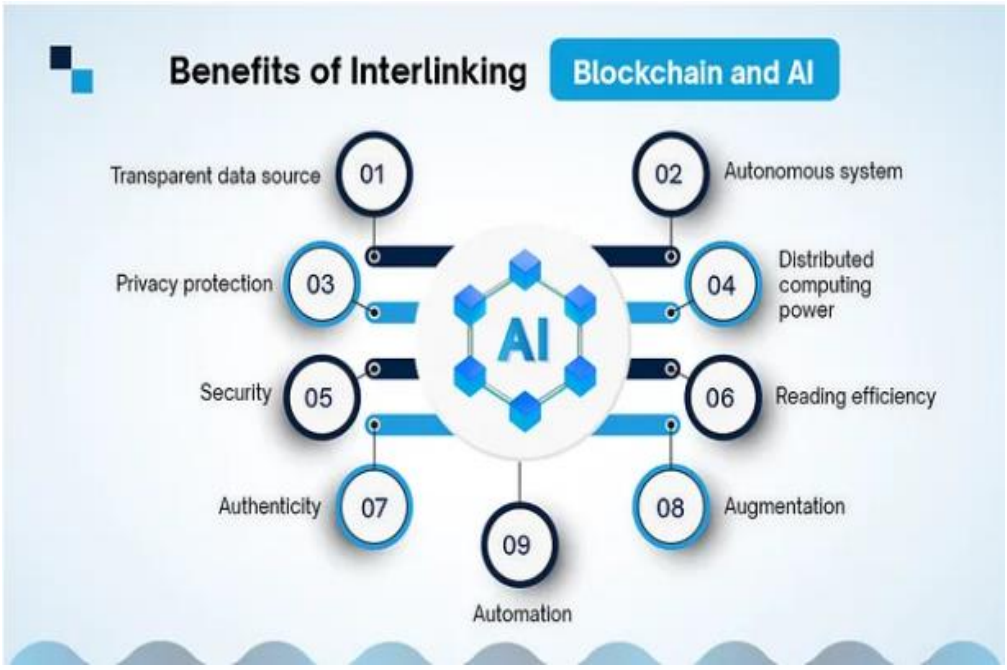

Fig. 4: Transformative Benefits of AI and Blockchain (Harshini et al., 2024, .p. 18589).

The integration of IoT with blockchain creates a robust framework for real-time monitoring and tracking in supply chains. IoT devices, such as GPS trackers, RFID tags, and smart sensors, capture real-time data on shipment conditions, such as temperature, humidity, and location. This data is securely recorded on the blockchain, ensuring transparency and immutability (Udeh et al., 2024). For instance, the sensors in the efficient cold chain logistics track changes in the temperature by the regulatory measures for perishable products. IoT improves total trackability capabilities, which help administrative divisions like food and

pharma. IBM Food Trust, in 2021 stated that they had cut down food wastage by 25% when they began using IoT with blockchain Supply Chain Sensing. Also, through increased asset traceability using IoT-integrated blockchain systems, cases of loss and theft in the supply chain are eliminated. The collaboration between these technologies provides stakeholders with actionable insights, enabling swift decision-making during disruptions (Ellahi et al., 2024).

Blockchain's decentralized structure complements Big Data analytics by providing a secure, scalable platform for managing and analyzing vast datasets. Big Data tools work with structured and unstructured data located on the blockchain to create value and select proper strategies to improve supply chain effectiveness. For instance, Big Data helps to define bottlenecks, variation forecasts and suppliers' efficiency. One of the considerable barriers to the adoption of blockchain is its scalability; Big Data technologies solve this problem by providing efficient ways of processing and storing data (Gogri, 2023). Global investment targeting the blockchain and Big Data integration to enhance the supply chain systems stood at $48.9 billion in 2029, but in 2024; it was $20.1 billion only (Research and Markets, 2024). Additionally, combining blockchain with Big Data enhances compliance reporting. In highly regulated industries like pharmaceuticals, Big Data analytics verify adherence to legal standards by analyzing blockchain-verified records, ensuring accuracy and reducing audit costs (Ellahi et al., 2024).

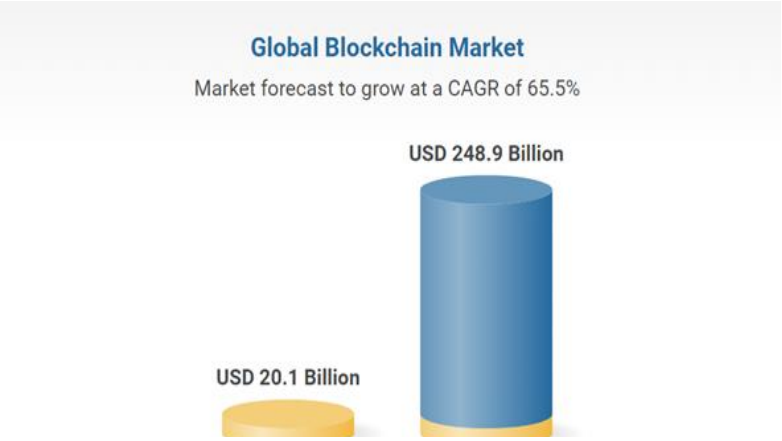

Fig. 5: The global blockchain market size is projected to grow from USD 20.1 billion in 2024 to USD 248.9 billion by 2029 (Research and Markets, 2024).

The collaboration of utilizing AI, IoT, and Big Data with blockchain technology as a solution applies a unique system that effectively encapsulates several key issues involving the supply chain. AI improves the accuracy of prediction and identifies potential frauds, IoT facilitates monitoring at present time, and Big Data guarantees the right use of data and its expansiveness. Combined, these technologies guarantee reliable, transparent, and optimized supply chain processes leading to a broader adaptation across global industries.

5. Current Trends and Innovations in Blockchain for Supply Chain Management

The establishment of blockchain consortia is one of the significant trends in the field due to the integration of the blockchain in the supply chain area, Decentralised financing of supply

chain operations is another trend that has resulted from the integration of blockchain and tokenization; it is another innovation that has been initiated by the integration of blockchain in the supply chain management operations. Blockchain consortia are when organizations come together to create more cross-platform blockchains to make the systems more compatible with each other across the supply chain. A well-known case is Aura Blockchain Consortium, which was created by such giants of the luxury industry as LVMH, Prada, Cartier and others (Cedrola et al., 2024). Owing to the above partnerships, Aura had signed over 50 luxury brands with a digital twine for over 40 million products, enhancing the overall credibility in the Luxury goods market (Aura Blockchain Consortium, 2024).

Decentralized finance (DeFi) leverages blockchain to provide financial services without traditional intermediaries, offering innovative solutions for supply chain financing. Through DeFi platforms, suppliers can tokenize invoices and access liquidity by selling these tokens to investors, thereby reducing reliance on traditional banking systems. This approach has been particularly beneficial for small and medium-sized enterprises (SMEs), which often face challenges in securing financing (Owolabi et al., 2024) A systematic review highlighted that blockchain-based SME financing, including DeFi solutions, addresses credit gaps and enhances financial inclusion. Additionally, DeFi platforms enable real-time settlement of transactions, reducing delays and enhancing cash flow within supply chains. This efficiency is crucial in industries with complex, multi-tiered supply chains, where traditional financing methods may be slow and cumbersome (Kumar et al., 2023).

Tokenization refers to the process of exchanging tangible assets or securities for digital tokens residing on a blockchain to propagate more supply chain finance models. In the same way that people can use their property as a form of collateral to obtain loans, inventory or invoices can be tokenized and sold under the blockchain, allowing companies to attract other investors. For instance, the process of tokenization of the assets of the supply chain makes it possible to divide ownership of the asset into fractions, thus increasing the efficiency in attracting funding from investors, diversifying the investor base and decreasing funding costs (Chen et al., 2023). In addition, tokenization increases the level of transparency and has high visibility since each token contains the necessary data about an asset, its source, the history of its possession, and conformity to existing laws. Such transparency means more trust with stakeholders and could improve the effectiveness and security of the supply chain (Series, 2020).

6. Challenges to Implementation

Implementing blockchain technology in supply chain management presents several challenges across technical, organizational, and regulatory domains.

There is still a growing problem of scalability when it comes to self-driving cars. Ethereum type of public blockchain can handle about 15 transactions per second, making it incapable of handling large volumes of supply chain transactions (Hafid et al., 2020). Furthermore, the adoption of the implementation of blockchain technology is challenging and costly because it is associated with significant modifications of the current legacy systems (Rafique & Qadir,

2024). The fourth important aspect is data privacy: while blockchain transparency is valuable, it can be challenged by business parties and place large amounts of emphasis on data confidentiality (Sedlmeir et al., 2022). Blockchain represents a cultural change in any organization, and the organization has to adapt to it. The barriers include resistance to adoption, absence of specialist skills in blockchain, and absence of consensual agreement among stakeholders (Kouhizadeh et al., 2021). According to Deloitte (2019), 43% of executives said that insufficient understanding was the main factor hindering blockchain adoption. Moreover, the capital investment needed for blockchain projects is high at the onset and can be a problem for most stakeholders, particularly SMEs (Wilson et al., 2024).

The regulatory landscape for blockchain is still evolving. Uncertainty regarding compliance with data protection laws, such as the General Data Protection Regulation (GDPR) in Europe, poses challenges. The immutable nature of blockchain conflicts with the "right to be forgotten" principle enshrined in GDPR (European Parliament, 2019). Additionally, the lack of standardized regulations across jurisdictions complicates cross-border supply chain operations (Zhang et al., 2019). To address scalability, organizations can explore Layer 2 solutions and permissioned blockchains, which offer higher transaction throughput and better control over data access (Khan et al., 2021). Investing in employee training and development can mitigate organizational resistance by building internal expertise. Collaborating with industry consortia can also facilitate knowledge sharing and establish best practices (Rejeb et al., 2021). Engaging with regulators proactively can help shape favourable policies and ensure compliance. Implementing privacy-preserving techniques, such as zero-knowledge proofs, can balance transparency with data confidentiality (Prasad et al., 2024).

While the implementation of blockchain in supply chains is fraught with challenges, a strategic approach that addresses technical, organizational, and regulatory barriers can pave the way for successful adoption.

7. Ethical, Social, and Environmental Implications

Blockchain technology has emerged as a pivotal tool in promoting sustainable practices, ensuring ethical sourcing, and preventing fraud within supply chains.

The integration of an immutable ledger makes Blockchain highly effective for making sustainability information open to the public for checks and authentication by various stakeholders. For example, the World Wildlife Fund organizes the OpenSC platform that uses blockchain to track foods that are produced environmentally friendly and fairly. According to WWF (2019), this initiative has improved consumer confidence and promoted the use of environmentally friendly products. When it comes to ethical issues like conflict minerals and child labour in industries blockchain provides solutions from origin to the end product. To ensure that diamonds sold through its network are not from war zones, De Beers, the premier diamond firm adopted the use of blockchain technology. MORE THAN ONE HUNDRED valuables such as diamonds have been tracked using this system hence the right steps are taken in sourcing the products hence increasing consumer trust (Anglo American, 2018). The

problem of Counterfeit goods is complex in many industries. Since blockchain is decentralized and secure from modifications, it is helpful against fraud (Potdar et al., 2023).

Blockchain technology plays a crucial role in promoting sustainability, ensuring ethical sourcing, and preventing fraud in supply chains. Its ability to provide transparency and traceability addresses critical ethical, social, and environmental challenges, fostering more responsible and trustworthy supply chain practices.

8. Key Findings

- Blockchain technology addresses key supply chain challenges such as lack of visibility, data silos, and counterfeiting, with global counterfeit losses estimated at $509 billion annually (OECD, 2024).
- Implementing blockchain has been shown to reduce fraud by 50% and enhance operational efficiency by up to 30% (Kamble et al., 2021).
- Integration with AI improves demand forecasting and fraud detection, with AI blockchain systems reducing fraud-related losses by 30% (Sarkar et al., 2024).
- IoT-enabled blockchain systems enhance real-time monitoring; for example, IBM Food Trust reduced food spoilage rates by 25% through real-time tracking (Ellahi et al., 2024).
- Big Data integration ensures scalability and actionable insights, with blockchain Big Data investments reaching $48.9 billion which was $20.1 billion in 2024 (Research and Markets, 2024).
- Case studies demonstrate blockchain's impact: Walmart reduced food traceability time from 6 days to 2.2 seconds, and TradeLens saved $50 million annually in administrative costs.
- Ethical and sustainable practices are supported by blockchain; De Beers tracked over 100 diamonds to ensure ethical sourcing, while Everledger traced 4 million diamonds to combat fraud (Anglo American, 2018).
- Scalability, regulatory uncertainties, and organizational resistance remain barriers, but strategies such as Layer 2 solutions, stakeholder collaboration, and privacy-preserving technologies are mitigating these challenges (Khan et al., 2021).

9. Conclusion

Blockchain technology has proven to be a transformative solution for enhancing end-to-end tracking and visibility in supply chain management. Through its decentralized, immutable, and transparent structure, blockchain addresses critical inefficiencies, such as data silos, fraud, and lack of real-time visibility. Key findings demonstrate that blockchain enhances traceability, reduces fraud by up to 50%, and improves operational efficiency by 30%. Case studies, including IBM Food Trust and Maersk's TradeLens, highlight blockchain's practical impact in reducing food spoilage, enhancing global shipping, and ensuring compliance with regulatory standards. Blockchain's integration with emerging technologies such as AI, IoT, and Big Data further amplifies its capabilities. Probabilistic analysis enhances decision-making, IoT devices support constant monitoring, and effective Big Data makes solutions efficient for large-scale

use. When used in collaboration these technologies provide a strong environment of transparency, efficiency, and accountability within supply chain partners. Referring to the formulated research question, it becomes clear that blockchain helps to establish a single source of truth that improves supply chain visibility end to end. It creates an environment for secure real-time updates through the supply chain network, minimizing delays, errors, and fraud. Over time, several industries will start using blockchain solutions, thus breaking supply chain barriers worldwide. More research should be done in addressing impediments to future developments: scalability, compliance, and organisation adoption to completely execute the blockchain impact in the modified supply chains.

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