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Leveraging blockchain for sustainable supply chain management: A data privacy and security perspective

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Abstract

This review examines how blockchain technology can be leveraged to enhance data privacy and security in sustainable supply chain management (SSCM). As global supply chains become increasingly complex and the demand for sustainability grows, ensuring data privacy and security has become a critical concern. Traditional supply chain systems often face challenges such as data breaches, lack of transparency, and difficulty in tracing products and materials. Blockchain technology, with its decentralized, immutable, and transparent architecture, offers a promising solution to these challenges. Blockchain can enhance data security by ensuring that data is tamper-proof, traceable, and encrypted, thus protecting sensitive information across the supply chain. It provides transparency while allowing permissioned access, ensuring that stakeholders can verify data without exposing confidential information. Furthermore, privacy-preserving technologies such as zero-knowledge proofs and homomorphic encryption allow verification of data without compromising its security. Smart contracts enable automated compliance with regulatory frameworks like GDPR, reducing the risk of human error and improving operational efficiency. The integration of blockchain in SSCM can improve traceability, transparency, and accountability, thereby promoting environmental and social sustainability. By tracking the origin and journey of goods, blockchain helps verify ethical sourcing practices and reduce carbon footprints. However, the technology also presents challenges, including scalability, integration with legacy systems, and cost considerations. Through case studies in industries such as food, textiles, and renewable energy, this review highlights the practical applications and benefits of blockchain for SSCM. It concludes that blockchain has the potential to revolutionize supply chain operations, but careful consideration must be given to overcoming its technical and financial barriers to widespread adoption.

Keywords: Blockchain; Supply Chain; Data Privacy; Security Perspective

1 Introduction

Sustainable supply chain management (SSCM) has become an increasingly critical focus in global markets, as businesses, consumers, and regulatory bodies alike place greater emphasis on environmental responsibility, social equity, and economic sustainability (Nwaimo *et al*., 2024; Daramola *et al*., 2024). SSCM refers to the strategic coordination of traditional supply chain activities, such as procurement, production, and distribution, while simultaneously addressing environmental and social concerns. These concerns include reducing carbon footprints, minimizing waste, promoting fair labor practices, and ensuring ethical sourcing (Eziamaka *et al*., 2024). The importance of SSCM has grown as global

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organizations aim to meet the demands of sustainability-conscious consumers and comply with tightening regulations aimed at addressing climate change and resource depletion.

However, the adoption of SSCM presents unique challenges, particularly in terms of data privacy and security. As supply chains become more complex and interconnected, vast amounts of sensitive data are exchanged between multiple stakeholders, including suppliers, manufacturers, and customers (Ikevuje *et al*., 2024; Ige *et al*., 2024). This data includes trade secrets, intellectual property, and sensitive personal information, all of which require protection from unauthorized access, breaches, and cyberattacks. Data privacy and security are therefore essential components of SSCM, as breaches can compromise not only the integrity of the supply chain but also the trust and loyalty of consumers and business partners.

Blockchain technology has emerged as a transformative solution for addressing these data privacy and security concerns while enhancing sustainability in supply chain management (Iyelolu *et al*., 2024). Blockchain is a decentralized, distributed ledger technology that allows for the transparent, secure, and immutable recording of transactions. By using cryptographic algorithms, blockchain ensures that data stored on its network is highly resistant to tampering and unauthorized access (Urefe *et al*., 2024). This level of transparency and security can significantly improve SSCM by enabling real-time tracking of goods, enhancing accountability, and providing verifiable information about the sustainability practices of various suppliers and stakeholders.

The primary purpose of this review is to examine how blockchain technology can address data privacy and security concerns in SSCM while promoting sustainable practices. The growing complexity of supply chains and the increased focus on sustainability demand robust solutions to ensure transparency, traceability, and ethical compliance. Blockchain's decentralized architecture offers significant potential in achieving these goals by providing a secure and tamper-proof platform for recording transactions, reducing the risk of data breaches, and enabling stakeholders to verify the sustainability of their supply chains (Okeke *et al*., 2023; Obiki-Osafiele *et al*., 2024). Furthermore, blockchain can facilitate efficient and transparent data sharing among participants in the supply chain, ensuring that sustainability claims are backed by verifiable data.

Despite the numerous advantages that blockchain can offer to SSCM, its successful integration presents several challenges (Agu *et al*., 2024). These include the technical complexity of blockchain implementation, scalability issues, the high energy consumption of certain blockchain models, and the reluctance of some supply chain participants to share sensitive data, even within a secure blockchain environment. Additionally, regulatory uncertainties surrounding blockchain adoption in different jurisdictions can pose barriers to widespread implementation. Therefore, this review also aims to highlight key challenges in integrating blockchain into SSCM and propose potential solutions to overcome these hurdles (Osundare and Ige, 2024). This review will explore how blockchain can enhance both data privacy and sustainability in supply chain management. It will evaluate the current state of blockchain adoption in SSCM, identify the main obstacles to its implementation, and suggest strategies for overcoming these challenges to ensure successful integration. By addressing data privacy and security concerns, blockchain has the potential to revolutionize SSCM and contribute to more sustainable, transparent, and ethical global supply chains.

2 Sustainable Supply Chain Management (SSCM)

Sustainable Supply Chain Management (SSCM) refers to the strategic integration of environmental, social, and economic sustainability goals into traditional supply chain processes such as procurement, production, logistics, and distribution. SSCM goes beyond the traditional focus on efficiency and profitability to ensure that supply chain operations contribute to broader sustainability objectives (Babatunde *et al*., 2024). These objectives include reducing environmental impacts, promoting fair labor practices, ensuring economic equity, and fostering long-term viability.

The principles of SSCM align with the three pillars of sustainability environmental, social, and economic. The environmental aspect emphasizes reducing the carbon footprint, minimizing waste, conserving natural resources, and promoting renewable energy use within the supply chain (Ajiva *et al*., 2024). The social dimension of SSCM addresses issues such as human rights, fair labor practices, and community development. Companies are increasingly expected to ensure that their suppliers adhere to ethical labor standards and contribute to social welfare in the communities where they operate. Finally, the economic aspect of SSCM is focused on creating long-term economic value for stakeholders by ensuring that the supply chain remains resilient, efficient, and capable of generating sustainable profits without exploiting resources or people.

Data plays a central role in achieving sustainability goals within SSCM by enhancing transparency, traceability, and accountability across the supply chain. Data transparency allows companies and their stakeholders to access accurate

and verifiable information about the sourcing, production, and distribution of goods (Uzougbo *et al*., 2024). Transparent data enables businesses to demonstrate their commitment to sustainability by providing evidence that products are sourced ethically, production processes are environmentally friendly, and workers are treated fairly. Traceability is another critical aspect of data's role in SSCM. It involves the ability to track the movement of goods throughout the supply chain, from raw material extraction to the final delivery of products (Esiri *et al*., 2024). Traceability ensures that companies can verify the origin and environmental impact of their materials, prevent counterfeiting, and ensure that suppliers adhere to sustainability standards. For example, in the food industry, traceability helps consumers verify whether a product is organic or sourced from a sustainable farm. Accountability is the third key aspect that data facilitates in SSCM. By collecting and analyzing data on supply chain activities, businesses can hold themselves and their suppliers accountable for meeting sustainability targets. This includes monitoring carbon emissions, waste generation, energy usage, and adherence to labor standards. Data-driven accountability ensures that companies can identify inefficiencies, improve performance, and demonstrate measurable progress toward sustainability goals (Osundare and Ige, 2024).

While data is essential for SSCM, it also presents significant challenges related to data privacy and security. The increased use of digital platforms and interconnected systems in supply chain management has made supply chains more vulnerable to data breaches, cyberattacks, and privacy violations (Akinsulire *et al*., 2024). Data privacy concerns arise from the need to protect sensitive information, such as intellectual property, trade secrets, and personal information about employees and customers. One of the main risks posed by data exposure in SSCM is the potential for cyberattacks. As supply chains become more digitized, hackers may target them to access confidential information, disrupt operations, or demand ransom payments. A successful cyberattack can result in data theft, operational downtime, reputational damage, and financial losses. For instance, if sensitive data about supplier contracts, pricing, or proprietary technologies are exposed, it could give competitors an unfair advantage or damage the company's market position. In addition to cyberattacks, data privacy breaches pose another significant risk in SSCM. Companies are increasingly required to comply with data protection regulations, such as the General Data Protection Regulation (GDPR) in the European Union, which mandates strict standards for handling personal data. In a supply chain context, personal data such as employee information, consumer purchase history, and supplier contracts may be vulnerable to unauthorized access. Privacy breaches can erode customer trust, lead to legal penalties, and compromise the integrity of the supply chain (Ezeh *et al*., 2024). Given these challenges, data security is a critical component of SSCM. Companies must implement robust security measures such as encryption, multi-factor authentication, and blockchain technology to ensure that data is protected from unauthorized access and tampering. Ensuring data privacy and security is essential for maintaining trust between supply chain partners and achieving long-term sustainability goals.

Sustainable supply chain management is essential for businesses looking to align with modern sustainability goals across environmental, social, and economic dimensions (Okeke *et al*., 2023). While data plays a key role in enhancing transparency, traceability, and accountability, it also introduces risks related to privacy and security. Addressing these challenges through secure data management and innovative technologies is crucial for the successful implementation of SSCM and the promotion of sustainable practices in global supply chains.

2.1 Blockchain Technology Overview

Blockchain is a decentralized, distributed ledger technology that enables the secure, transparent, and immutable recording of transactions across a network of participants (Uzougbo *et al*., 2024). Its key features include decentralization, immutability, transparency, and consensus mechanisms, each of which plays a crucial role in its operation and potential applications, particularly in supply chain management. Decentralization is the defining characteristic of blockchain technology. Unlike traditional systems where a central authority manages and validates transactions, blockchain operates through a distributed network of nodes, where each participant holds a copy of the ledger (Osundare and Ige, 2024). This structure eliminates the need for intermediaries, enhancing efficiency and reducing the risk of single points of failure. In supply chains, decentralization allows all stakeholders from suppliers to manufacturers to customers to access the same information without relying on a central entity, thereby fostering trust and collaboration.

Immutability refers to the irreversible nature of transactions once they are recorded on the blockchain. Each transaction is time-stamped, encrypted, and linked to previous entries in the chain, creating an unalterable history of data. This feature is especially valuable in supply chain management, where the authenticity of records such as the origin of raw materials or compliance with sustainability standards must be verifiable (Okatta *et al*., 2024). Once data is added to the blockchain, it cannot be tampered with, ensuring a high level of data integrity. Transparency in blockchain means that all participants in the network have access to the same version of the ledger, promoting openness and trust among parties. In the context of supply chain management, transparency enables stakeholders to monitor the movement of

goods in real-time, verify the ethical sourcing of materials, and ensure compliance with sustainability goals. For example, consumers can track a product's journey from production to delivery, allowing them to make informed purchasing decisions. Consensus mechanisms are algorithms used by blockchain networks to agree on the validity of transactions before they are added to the ledger. Common mechanisms include Proof of Work (PoW), Proof of Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT). These mechanisms ensure that only valid transactions are recorded, preventing fraud and double-spending. In supply chain management, consensus mechanisms contribute to the reliability and security of the system, as all participants must agree on the validity of information before it is entered into the blockchain (Daramola *et al*., 2024).

There are two primary types of blockchain networks: public and private, both of which have implications for data privacy and security in supply chain management (Efunniyi *et al*., 2024). Public blockchains are open to anyone and operate in a fully decentralized manner. Bitcoin and Ethereum are examples of public blockchains. In public blockchain systems, anyone can participate in the network, validate transactions, and access the ledger. While this ensures maximum transparency, it also raises concerns about data privacy, as sensitive information could potentially be viewed by unauthorized parties. In supply chains, public blockchains may be useful when transparency and public verification are priorities, such as in tracing the ethical sourcing of materials or ensuring compliance with sustainability standards. Private blockchains, on the other hand, are restricted to a specific group of participants. They are typically used by organizations or consortia where only authorized entities can access and validate transactions. Private blockchains provide greater control over data privacy and are often preferred for use in supply chains where confidentiality is critical, such as in managing supplier contracts, proprietary production techniques, or sensitive financial information (Adeniran *et al*., 2022). Private blockchains allow organizations to reap the benefits of blockchain's immutability and traceability while maintaining greater control over who can view and edit the data. In many cases, hybrid models that combine features of both public and private blockchains are used to balance transparency and privacy. These models allow certain parts of the supply chain to remain publicly visible while keeping sensitive data restricted to authorized participants.

Blockchain technology has significant applications in supply chain management, particularly in enhancing traceability, transparency, and sustainability. The decentralized, immutable, and transparent nature of blockchain makes it an ideal solution for addressing challenges related to data accuracy, accountability, and ethical compliance (Obiki-Osafiele *et al*., 2024). Traceability is one of the most widely cited applications of blockchain in supply chains. By using blockchain, companies can track the movement of goods throughout the entire supply chain, from raw material extraction to final product delivery. This ensures that each step of the process is accurately recorded and that the origin and movement of materials can be verified. By providing real-time visibility into the movement of goods, companies can demonstrate to consumers and regulatory bodies that they are adhering to environmental and social standards. This is particularly important for industries like fashion and electronics, where consumers are increasingly concerned about the ethical sourcing of materials and the labor practices involved in production. Sustainability is another key area where blockchain can make a difference. Blockchain enables companies to track their carbon emissions, energy use, and waste generation throughout the supply chain. This data can be shared with stakeholders to demonstrate progress toward sustainability goals, such as reducing greenhouse gas emissions or transitioning to renewable energy sources (Agu *et al*., 2024). Additionally, blockchain can be used to verify that suppliers are meeting environmental regulations and sustainability certifications.

Blockchain technology offers transformative potential for supply chain management by providing decentralized, immutable, and transparent platforms that enhance traceability, accountability, and sustainability (Scott *et al*., 2024). Whether through public or private blockchains, the application of this technology can address significant challenges related to data privacy, security, and ethical compliance in modern supply chains. By leveraging blockchain, organizations can build more resilient, transparent, and sustainable supply chains that meet the demands of consumers, regulators, and stakeholders alike.

2.2 Data Privacy and Security in Blockchain-Based Supply Chains

Blockchain technology offers significant advancements in data privacy, particularly within supply chains (Abdul-Azeez *et al*., 2024). One of the primary benefits of blockchain is its decentralization, which reduces reliance on centralized systems that are often vulnerable to breaches and unauthorized access. In traditional supply chains, sensitive data is typically stored in centralized databases managed by a single entity. This centralization creates a single point of failure, making it easier for hackers to access and manipulate the data. In contrast, blockchain distributes data across a network of nodes, where each participant retains a copy of the entire ledger. This distribution ensures that no single entity has control over the data, enhancing privacy by making unauthorized access more difficult. Additionally, blockchain employs cryptographic techniques to secure data. Each transaction is encrypted and linked to previous entries using

cryptographic hashes, creating an immutable record that is resistant to tampering. This cryptographic foundation not only protects the integrity of the data but also ensures that sensitive information, such as supplier contracts or customer details, remains confidential. Only authorized participants with the appropriate cryptographic keys can access specific data on the blockchain, effectively safeguarding privacy while enabling transparency in supply chain transactions (Ogunleye, 2024).

Data security is a critical concern in supply chain management, and blockchain addresses this through its inherent features. One of the most notable aspects of blockchain is its immutability, which ensures that once a transaction is recorded, it cannot be altered or deleted. This feature protects against data tampering, as any attempt to modify past records would require the consensus of the majority of network participants (Esiri *et al*., 2024). In supply chains, this immutability is crucial for maintaining accurate records of product provenance, compliance with regulations, and adherence to sustainability practices. Moreover, blockchain enhances security protocols through its distributed control structure. Unlike centralized databases, where data can be vulnerable to attacks, the distributed nature of blockchain makes it more resilient. Each node in the network validates transactions, and any malicious activity would require controlling a significant portion of the network, which is economically and logistically challenging. This decentralized validation process not only strengthens security but also fosters trust among supply chain participants, as all parties can independently verify transactions.

While blockchain inherently improves data privacy and security, additional privacy-preserving technologies can further enhance these aspects. Techniques such as zero-knowledge proofs, homomorphic encryption, and differential privacy provide innovative solutions for maintaining confidentiality without compromising the integrity of the data (Akinsulire *et al*., 2024). Zero-knowledge proofs allow one party to prove knowledge of a particular piece of information without revealing the information itself. This is particularly useful in supply chains where participants need to verify compliance or legitimacy without disclosing sensitive data. For example, a supplier could prove that their materials meet certain sustainability standards without revealing proprietary sourcing information. Homomorphic encryption allows computations to be performed on encrypted data without needing to decrypt it first. This capability enables supply chain participants to collaborate on data analysis and decision-making without exposing their sensitive information, thus maintaining privacy while leveraging the benefits of shared data. Differential privacy adds another layer of protection by introducing randomness into datasets, ensuring that individual entries cannot be identified, even when aggregated (Uzougbo *et al*., 2024). This technique is valuable in supply chains that involve sharing operational metrics or consumer behavior data while protecting the privacy of individual participants.

When considering blockchain implementations for supply chains, the choice between permissioned and public blockchains can significantly impact data privacy (Ogedengbe, 2023). Public blockchains, such as Bitcoin and Ethereum, offer complete transparency but may not provide adequate privacy for sensitive business information. In contrast, permissioned blockchains restrict access to a predefined set of participants, allowing organizations to maintain tighter control over who can view and interact with the data. Permissioned blockchains can balance privacy, security, and transparency by allowing only authorized entities to participate in the network. This selective access ensures that sensitive information remains confidential while still enabling transparency among trusted participants. Data privacy and security are paramount in blockchain-based supply chains, and the technology offers robust solutions to address these concerns. Through decentralization, cryptographic techniques, and enhanced security protocols, blockchain enhances data privacy and protects against tampering (Okeke *et al*., 2022). Furthermore, privacy-preserving technologies and the choice between permissioned and public blockchains provide organizations with the flexibility to tailor their approaches to privacy and security based on their specific needs. By leveraging blockchain, supply chains can achieve greater efficiency, transparency, and resilience while safeguarding sensitive information in an increasingly interconnected world.

2.3 Smart Contracts and Automated Data Privacy Compliance

Smart contracts are self-executing agreements with the terms of the contract directly written into code, which are stored and executed on a blockchain. In the context of supply chains, smart contracts play a pivotal role in automating data security protocols and privacy policies (Ezeh *et al*., 2024). By leveraging the decentralized and immutable nature of blockchain, these contracts can facilitate secure and transparent transactions between parties while ensuring compliance with established data privacy standards.

One of the primary advantages of smart contracts in supply chains is their ability to automate the enforcement of data security protocols. This automation not only minimizes the risk of human error but also enhances the overall efficiency of data handling. By specifying conditions for data access and sharing within the contract, organizations can ensure that sensitive information is only available to authorized parties and that data privacy is maintained throughout the supply

chain process (Ezeafulukwe *et al*., 2024). Moreover, smart contracts can monitor compliance with privacy policies in real-time. For example, if a data-sharing agreement stipulates that customer information cannot be retained for longer than a specified period, the smart contract can automatically delete the data once the retention period expires. This automated enforcement reduces the burden on organizations to manually monitor compliance, allowing them to focus on other critical aspects of their operations while ensuring that privacy policies are upheld (Nwaimo *et al*., 2024).

As data privacy regulations such as the General Data Protection Regulation (GDPR) become more stringent, organizations must ensure that their supply chains adhere to these frameworks. Smart contracts can play a vital role in facilitating compliance with these regulatory requirements by embedding legal obligations directly into the contract code (Ajiga *et al*., 2024). Smart contracts can automate the processes involved in obtaining and managing consent for data collection and processing. By embedding consent mechanisms within the contract, organizations can ensure that they only process data when explicit consent is provided by the individual. Additionally, smart contracts can facilitate the right to be forgotten, a key component of GDPR, by automatically deleting personal data upon request or when it is no longer necessary for processing. Furthermore, smart contracts can enhance accountability and traceability within the supply chain. By recording all data processing activities on the blockchain, organizations can create an immutable audit trail that demonstrates compliance with regulatory frameworks. This transparency not only helps organizations manage compliance more effectively but also provides regulators with verifiable evidence of adherence to privacy laws, thereby mitigating the risk of penalties and reputational damage (Okatta *et al*., 2024; Ekemezie and Digitemie, 2024).

Automated reporting and auditing processes are essential for maintaining compliance with data privacy regulations and ensuring that organizations can adapt to evolving legal landscapes. Smart contracts streamline these compliance processes by automatically generating reports and facilitating audits based on predefined criteria (Abdul-Azeez *et al*., 2024). This real-time tracking enables organizations to generate compliance reports on demand, reducing the time and resources required for manual reporting. By automating reporting processes, organizations can maintain accurate records of their data handling practices, which is crucial for demonstrating compliance during audits.

Additionally, blockchain technology enhances the integrity of audit trails. Since all transactions and data processing activities are recorded in a tamper-proof manner, auditors can trust the accuracy and authenticity of the information presented. This level of transparency simplifies the auditing process and fosters trust among stakeholders, as all parties can verify compliance with data privacy regulations (Esiri *et al*., 2023). Moreover, smart contracts can trigger automatic audits based on specific events or timelines, ensuring that compliance is continuously monitored. For example, if a smart contract detects a potential breach of privacy policies, it can initiate an immediate audit to assess the situation and take corrective actions if necessary. This proactive approach to compliance not only enhances data privacy but also helps organizations identify and mitigate risks before they escalate (Abdul-Azeez *et al*., 2024).

Smart contracts offer a powerful solution for automating data privacy compliance within supply chains. By facilitating the enforcement of data security protocols, ensuring adherence to regulatory frameworks such as GDPR, and streamlining reporting and auditing processes, smart contracts enhance the efficiency and effectiveness of data privacy measures. As organizations increasingly rely on digital solutions to manage their supply chains, the integration of smart contracts will play a crucial role in safeguarding sensitive information while ensuring compliance with evolving privacy regulations. By leveraging the capabilities of smart contracts, businesses can build more resilient and secure supply chains that prioritize data privacy and security in an increasingly interconnected world (Okeke *et al*., 2023).

2.4 Benefits of Blockchain for Sustainable Supply Chain Management

As global markets increasingly prioritize sustainability, the integration of blockchain technology into supply chain management offers transformative benefits (Daramola *et al*., 2024). By enhancing data security and privacy, improving traceability and transparency, strengthening trust and accountability, and promoting environmental and social sustainability, blockchain can significantly advance sustainable practices across industries.

One of the foremost benefits of blockchain technology is its ability to enhance data security and privacy. Traditional supply chains often rely on centralized databases, which can be vulnerable to data breaches and unauthorized access. In contrast, blockchain's decentralized architecture distributes data across a network of nodes, making it inherently more secure. Each transaction recorded on the blockchain is encrypted and linked to previous transactions, creating a secure and immutable record (Scott *et al*., 2024). This structure significantly reduces the risks associated with data breaches, as unauthorized entities would need to compromise multiple nodes to alter information. Moreover, blockchain enables granular access control, allowing organizations to define who can view and interact with specific data. By granting access only to authorized participants, companies can safeguard sensitive information while maintaining the privacy of stakeholders. This enhanced security is particularly important in supply chains that handle

confidential data, such as customer information or proprietary processes. As organizations prioritize data privacy, blockchain offers a robust solution that protects against potential cyber threats and fosters confidence among participants (Akinsulire *et al*., 2024).

Blockchain technology also improves traceability and transparency within supply chains. The decentralized nature of blockchain allows for real-time tracking of products and materials at every stage of the supply chain. Each transaction, from raw material sourcing to final delivery, is recorded on the blockchain, creating an immutable history of the product's journey. This level of traceability is crucial for ensuring compliance with regulations, verifying the authenticity of products, and monitoring adherence to sustainability standards. Similarly, in the fashion industry, brands can use blockchain to verify that their materials are sourced ethically and sustainably. By providing transparent access to information, blockchain empowers consumers to make informed purchasing decisions and fosters accountability among supply chain participants (Nwosu, 2024).

The secure and transparent nature of blockchain fosters trust and accountability among stakeholders. In traditional supply chains, the lack of visibility can lead to skepticism regarding the authenticity and integrity of products. Blockchain addresses this issue by providing a shared, immutable ledger that all participants can access (Iwuanyanwu *et al*., 2024). This transparency reduces the potential for fraud and misrepresentation, as every transaction is verifiable by all parties involved. By enabling secure and transparent transactions, blockchain strengthens relationships between suppliers, manufacturers, retailers, and consumers. Trust is particularly vital in sustainable supply chains, where stakeholders must rely on one another to adhere to ethical practices and regulatory requirements. When organizations can verify compliance through blockchain, it builds confidence among partners and consumers, ultimately leading to stronger collaborations and long-term relationships (Ikevuje *et al*., 2024).

Blockchain technology is instrumental in promoting environmental and social sustainability within supply chains (Samira *et al*., 2024). By providing a transparent and immutable record of sustainability practices, blockchain enables organizations to verify and track their efforts toward ethical sourcing, carbon footprint reduction, and compliance with environmental regulations. This information can be made accessible to stakeholders, demonstrating the organization's commitment to sustainable practices. Furthermore, blockchain can facilitate the tracking of carbon emissions throughout the supply chain, enabling organizations to identify areas for improvement and work towards emissions reduction targets. In addition to environmental sustainability, blockchain can support social sustainability by verifying fair labor practices and ensuring that workers' rights are upheld throughout the supply chain. By embedding social criteria into smart contracts, organizations can enforce ethical labor practices, ensuring that suppliers comply with standards for fair wages, safe working conditions, and non-discrimination (Ezeafulukwe *et al*., 2024). This capability not only promotes social responsibility but also enhances brand reputation and consumer trust.

The integration of blockchain technology into supply chain management offers numerous benefits that significantly advance sustainable practices (Nwaimo *et al*., 2024). By enhancing data security and privacy, improving traceability and transparency, strengthening trust and accountability, and promoting environmental and social sustainability, blockchain provides organizations with the tools they need to build resilient and responsible supply chains. As industries increasingly prioritize sustainability, leveraging blockchain technology will be essential for driving positive change and fostering a more sustainable future.

2.5 Challenges and Limitations of Blockchain for Data Privacy and Security

While blockchain technology holds immense potential for enhancing data privacy and security, it is not without its challenges and limitations (Akinsulire *et al*., 2024). Issues such as scalability, integration with legacy systems, cost and complexity, and data governance must be addressed to fully realize the benefits of blockchain in data privacy and security.

One of the primary challenges facing blockchain technology is scalability. As the number of transactions increases, maintaining both security and scalability within blockchain networks becomes increasingly difficult. Most public blockchains, such as Bitcoin and Ethereum, have faced significant scalability issues, where transaction throughput can be limited by the time it takes for nodes to reach consensus (Esiri *et al*., 2023). This limitation results in slower transaction speeds and higher fees, which can hinder the practicality of blockchain for real-time applications, particularly in supply chain management. To address these scalability issues, various solutions have been proposed, such as sharding, layer-two protocols, and off-chain transactions. However, these solutions often involve trade-offs that can impact the security and decentralization of the network. For example, while layer-two solutions can enhance transaction speed, they may also introduce new vulnerabilities or reduce the transparency inherent in a fully

decentralized system. Balancing security and scalability remains a critical challenge for the widespread adoption of blockchain technology in data privacy and security contexts (Nwosu *et al*., 2024).

Integrating blockchain with existing legacy systems presents another significant challenge. Many organizations rely on established supply chain technologies that may not be compatible with blockchain solutions (Ekemezie *et al*., 2024). The integration process can be complex and resource-intensive, requiring extensive modifications to existing systems or the development of new interfaces. This complexity can deter organizations from adopting blockchain, particularly if they are already invested in legacy systems that meet their current needs. Moreover, the lack of standardized protocols and interoperability between different blockchain platforms adds another layer of difficulty. Organizations may find themselves locked into a specific blockchain solution, making it challenging to switch or integrate with other technologies in the future. To overcome these challenges, a concerted effort is needed to develop universal standards and protocols that facilitate the integration of blockchain with existing supply chain technologies.

The financial and operational costs of implementing blockchain technology can also pose significant barriers to its adoption. Developing, deploying, and maintaining a blockchain network can be expensive, particularly for small and medium-sized enterprises (SMEs) that may lack the necessary resources (Abdul-Azeez *et al*., 2024). Costs associated with infrastructure, technical expertise, and ongoing support can accumulate quickly, making blockchain a less attractive option for organizations with limited budgets. Furthermore, the complexity of blockchain technology itself can be a barrier to entry. Organizations may require specialized knowledge to understand and effectively implement blockchain solutions. The steep learning curve can deter organizations from adopting blockchain, particularly if they do not have access to experts or training resources. To promote the adoption of blockchain technology, stakeholders must work towards simplifying its implementation and demonstrating its cost-effectiveness over time.

Ensuring proper governance of data on decentralized networks is a critical challenge that must be addressed for blockchain to be effective in enhancing data privacy and security (Olaleye *et al*., 2023). In a decentralized blockchain network, control over data is distributed among multiple participants, which can complicate data governance. Organizations must navigate issues related to data ownership, access rights, and compliance with regulatory frameworks. Data governance frameworks must be established to define roles and responsibilities within blockchain networks (Okeke *et al*., 2023). This includes determining who has the authority to access, modify, or delete data, as well as how data breaches or unauthorized access will be handled. Additionally, organizations must ensure that they comply with regulations such as the General Data Protection Regulation (GDPR), which mandates strict controls over personal data. The decentralized nature of blockchain can complicate compliance efforts, as organizations may struggle to identify responsible parties in the event of a data breach or privacy violation. Furthermore, the immutability of blockchain poses challenges for data governance. While immutability enhances data integrity, it can also create complications when it comes to correcting errors or fulfilling data subject requests under privacy regulations. Organizations must develop mechanisms to address these challenges while ensuring that data governance practices align with legal requirements (Ezeh *et al*., 2024).

Despite the numerous benefits blockchain technology offers for data privacy and security, challenges such as scalability, integration with legacy systems, cost and complexity, and data governance must be addressed to enable its effective implementation. As organizations continue to explore the potential of blockchain, it is essential to develop strategies and solutions that mitigate these challenges (Ezeafulukwe *et al*., 2024). By fostering collaboration among stakeholders, establishing industry standards, and enhancing education and training on blockchain technology, the adoption of blockchain for data privacy and security can be accelerated, ultimately leading to more secure and efficient supply chain management.

2.6 Case Studies

Blockchain technology is increasingly being adopted across various industries as organizations seek to enhance sustainability, traceability, and data integrity within their supply chains. This explores three notable case studies: the application of blockchain in food supply chain sustainability, textile supply chains, and renewable energy (Nwaimo *et al*., 2024). Each case illustrates how blockchain can address critical challenges while ensuring data privacy and security.

The food industry has faced numerous challenges related to traceability, safety, and sustainability. In response, companies are leveraging blockchain technology to enhance transparency and accountability throughout the food supply chain. A prominent example is Walmart's collaboration with IBM on the Food Trust blockchain. This initiative aims to create a shared, decentralized ledger that enables real-time tracking of food products from farm to table. By using blockchain, Walmart can enhance traceability, allowing consumers and stakeholders to verify the origin of their food products (Ajiga *et al*., 2024). Additionally, the blockchain securely records data related to farming practices,

enabling companies to verify compliance with sustainability standards, such as organic farming certifications. The integration of blockchain not only improves food safety and transparency but also addresses data privacy concerns. Each participant in the supply chain has access to only the information relevant to their role, protecting sensitive data while maintaining transparency. This capability is crucial in building consumer trust, as customers increasingly seek assurance that their food is sourced ethically and sustainably (Eziamaka *et al*., 2024).

The textile industry faces ongoing scrutiny regarding ethical sourcing and supply chain transparency (Samira *et al*., 2024). Brands such as Patagonia and H&M have adopted blockchain technology to secure sensitive supplier and product data while promoting ethical practices. For instance, H&M launched a blockchain pilot project in collaboration with the startup VeChain, aimed at improving traceability and transparency in its supply chain. Through this initiative, H&M can track the origin of its raw materials, ensuring that cotton, for example, is sourced from suppliers who adhere to fair labor practices. By recording each transaction on a blockchain, the company provides consumers with access to verified information about the product's journey, including details about suppliers and production processes. This level of transparency not only enhances consumer confidence but also encourages suppliers to comply with ethical sourcing standards, knowing that their practices will be publicly scrutinized. Moreover, the use of blockchain allows brands to protect sensitive data related to supplier relationships and pricing (Scott *et al*., 2024). By using private or permissioned blockchains, companies can control who has access to specific information while maintaining the integrity of the data. This capability is vital in preventing unauthorized access and ensuring that competitive advantages are safeguarded.

The renewable energy sector is increasingly utilizing blockchain technology to track carbon credits and energy usage while ensuring data integrity. One notable example is Power Ledger, a blockchain-based platform that enables peer-to-peer energy trading. Through this platform, consumers can buy and sell excess renewable energy directly from one another, promoting the adoption of sustainable energy practices (Akinsulire, 2012). Power Ledger uses blockchain to record each transaction securely, ensuring that data related to energy production, consumption, and carbon credits is accurate and transparent. This capability allows consumers to track their carbon footprints and verify the sustainability of their energy sources. By incentivizing renewable energy usage, the platform contributes to overall carbon reduction efforts and fosters a more sustainable energy ecosystem. Additionally, the platform ensures data integrity by providing a tamper-proof record of energy transactions. This transparency enhances trust among participants, as all transactions are visible and verifiable. As governments and organizations worldwide work toward achieving net-zero emissions, the ability to accurately track and verify carbon credits through blockchain will be crucial in promoting accountability and transparency in the renewable energy sector.

2.7 Future Directions and Innovations in Blockchain Technology

As blockchain technology continues to evolve, its applications in various sectors, particularly in supply chain management, are becoming more sophisticated (Ogunleye, 2024). Future directions and innovations in this field are focused on enhancing data privacy, integrating artificial intelligence, adapting to evolving regulations, and addressing interoperability challenges.

The demand for enhanced data privacy in blockchain applications has led to the development of advanced privacy-preserving technologies (Ezeh *et al*., 2024). One such technique is secure multi-party computation (MPC), which allows multiple parties to jointly compute a function over their inputs while keeping those inputs private. This method can be particularly valuable in supply chains, where sensitive data must be shared among different stakeholders without compromising individual privacy. MPC enables organizations to collaborate on data-driven decisions, such as demand forecasting or supply chain optimization, while ensuring that sensitive information remains confidential. Additionally, other privacy-enhancing techniques, such as zero-knowledge proofs and homomorphic encryption, are gaining traction in the blockchain space. These innovations allow parties to prove the validity of a transaction without revealing any underlying data, further bolstering privacy and security in blockchain networks.

The integration of artificial intelligence (AI) and machine learning (ML) into blockchain technology presents exciting opportunities for enhancing security and privacy in blockchain-based supply chains (Iwuanyanwu *et al*., 2024). AI can analyze vast amounts of data generated within blockchain networks, identifying patterns and anomalies that may indicate security breaches or fraudulent activities. By leveraging machine learning algorithms, organizations can enhance their ability to detect and respond to threats in real time. Moreover, AI can optimize blockchain operations by improving consensus mechanisms and transaction processing efficiency. For instance, AI algorithms can predict network congestion and adjust transaction fees accordingly, ensuring that the blockchain operates smoothly even during peak periods. The synergy between AI and blockchain not only enhances security and efficiency but also enables organizations to make more informed decisions based on data-driven insights (Reis *et al*., 2024).

As blockchain technology becomes more mainstream, regulatory frameworks surrounding data privacy and sustainability are also evolving (Esiri *et al*., 2024). Governments and regulatory bodies are increasingly recognizing the need to establish guidelines that address the unique challenges posed by blockchain technology. For instance, regulations like the General Data Protection Regulation (GDPR) in Europe have significant implications for how organizations manage personal data on blockchain networks. Future regulatory trends will likely focus on creating balanced frameworks that promote innovation while ensuring consumer protection and data privacy. This includes guidelines on how to handle data rights, consent, and accountability within blockchain systems. Additionally, regulations will need to address sustainability concerns, encouraging organizations to adopt environmentally friendly practices in their blockchain operations. As regulatory landscapes continue to evolve, organizations will need to stay informed and adapt their blockchain strategies accordingly (Ogunleye, 2024).

One of the significant challenges facing the blockchain ecosystem is interoperability the ability of different blockchain networks to communicate and interact with one another (Abdul-Azeez *et al*., 2024). As the number of blockchain platforms continues to grow, the need for cross-platform integration becomes increasingly important. Achieving interoperability would enable organizations to leverage the unique strengths of various blockchains, facilitating seamless data exchange and collaboration across networks. Innovative solutions are emerging to address this challenge, including the development of interoperability protocols and frameworks that allow different blockchains to connect and share data. Projects like Polkadot and Cosmos are at the forefront of this movement, enabling a decentralized ecosystem where blockchains can communicate and collaborate efficiently. By fostering interoperability, organizations can enhance their supply chain management processes, improve data accessibility, and promote greater innovation within the blockchain space (Ikevuje *et al*., 2024).

The future of blockchain technology is filled with promising directions and innovations that have the potential to transform supply chain management and beyond. Advanced privacy-preserving technologies, the integration of AI and machine learning, evolving regulatory frameworks, and addressing interoperability challenges will play critical roles in shaping the blockchain landscape (Agu *et al*., 2024). As organizations continue to explore and implement these innovations, they will unlock new opportunities for enhancing data privacy, security, and sustainability, paving the way for a more efficient and responsible future in blockchain-based supply chains.

3 Conclusion

In summary, blockchain technology has emerged as a transformative force in enhancing data privacy and security within sustainable supply chain management (SSCM). By leveraging its key features, such as decentralization, immutability, and transparency, blockchain addresses critical challenges related to data privacy and security. It allows organizations to share information securely while ensuring that sensitive data remains protected, thereby fostering trust among stakeholders. The integration of blockchain in SSCM not only enhances data integrity but also promotes accountability and traceability, essential components for achieving sustainability goals.

The potential of blockchain to transform sustainable supply chains is substantial. By facilitating real-time tracking of products and materials, blockchain enables organizations to verify the authenticity of their sourcing practices and monitor compliance with sustainability standards. This capability not only supports ethical sourcing but also enhances the overall efficiency and resilience of supply chains. As consumers increasingly demand transparency and sustainability, blockchain offers a powerful tool for organizations to demonstrate their commitment to responsible practices.

However, addressing the future challenges and opportunities associated with blockchain adoption in SSCM is crucial for maximizing its benefits. Scalability, integration with legacy systems, and data governance remain significant hurdles that organizations must overcome. Moreover, evolving regulatory frameworks will require ongoing adaptation to ensure compliance while fostering innovation. By actively engaging with these challenges and investing in the development of advanced technologies, organizations can harness the full potential of blockchain to create more sustainable and secure supply chains. The journey toward widespread blockchain adoption in SSCM is a collaborative effort that will shape the future of responsible business practices in an increasingly interconnected world.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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