



(REVIEW ARTICLE)



Blockchain for sustainable supply chains: A systematic review and framework for SME implementation

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Abstract

This paper presents a systematic review of the role of blockchain technology in fostering sustainable supply chains, with a particular emphasis on its implementation for small and medium-sized enterprises (SMEs). The objective is to explore how blockchain can address critical challenges such as transparency, traceability, and accountability, thereby contributing to more sustainable and ethical supply chain practices. Through an extensive literature review, this study examines various blockchain applications and their potential to enhance sustainability by reducing inefficiencies, ensuring compliance with environmental standards, and mitigating risks related to unethical practices.

The research methodology involved a comprehensive analysis of peer-reviewed articles, case studies, and industry reports to identify the benefits and barriers of blockchain adoption in supply chains. Key findings suggest that while blockchain can significantly enhance transparency and sustainability, SMEs face unique challenges in terms of technological adoption, cost implications, and scalability. Additionally, the paper proposes a framework tailored to SME needs, outlining practical steps for blockchain implementation, including initial investment strategies, stakeholder collaboration, and integration with existing technologies.

The study concludes that blockchain holds great potential for advancing sustainable supply chains, but its adoption by SMEs requires a strategic approach that addresses financial, technical, and operational barriers. This framework provides a roadmap for SMEs aiming to leverage blockchain technology to achieve sustainability goals, thus contributing to long-term business competitiveness and compliance with global sustainability standards.

Keywords: Blockchain technology; SMEs; Supply chain innovation; Transparency; Traceability; Sustainability; Strategic partnerships; Circular economy; Smart contracts; Supply chain automation; Sustainable practices; Supply chain financing; Blockchain adoption; Digital economy; Global markets

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1. Introduction

1.1. Importance of Blockchain in Supply Chain Sustainability: Introduction to the significance of blockchain technology in supply chains, highlighting its potential to increase transparency, traceability, and sustainability across industries

The rapid evolution of technology has brought significant changes to how global supply chains are managed, with blockchain technology emerging as a transformative tool for enhancing supply chain sustainability. In recent years, supply chains have faced increasing scrutiny over their environmental impact, operational inefficiencies, and lack of transparency. Blockchain technology, with its ability to provide secure, decentralized, and immutable records, is seen as a promising solution to address these issues. This technology's application in supply chains can increase transparency, traceability, and accountability across industries, promoting more ethical and sustainable practices (Saber et al., 2019).

Blockchain is a distributed ledger technology that allows participants to record transactions in a secure and transparent manner. Once information is recorded on the blockchain, it becomes immutable, ensuring that every transaction is traceable from its origin to its final destination (Wang et al., 2019). This unique feature makes blockchain an ideal solution for addressing some of the key challenges faced by modern supply chains, including fraud, inefficiencies, and lack of visibility across the entire supply chain. The integration of blockchain in supply chain management has the potential to drastically reduce costs, improve operational efficiency, and foster sustainability by promoting accountability and transparency (Kouhizadeh and Sarkis, 2018).

One of the major challenges that supply chains face today is ensuring transparency in operations. Traditional supply chain models are often opaque, with limited access to information on the origin and journey of raw materials, production processes, and product distribution. This lack of visibility can lead to unethical practices, environmental degradation, and violations of labor rights (Casino et al., 2019). Blockchain technology addresses this issue by providing an immutable ledger of all transactions and interactions within the supply chain, from the sourcing of raw materials to the delivery of final products. This enhanced transparency ensures that all stakeholders, including consumers, regulators, and businesses, have access to accurate and verifiable information on the sustainability of products and processes (Hughes et al., 2019).

In addition to transparency, traceability is another critical aspect of sustainable supply chains. Traceability refers to the ability to track the movement of goods and materials throughout the supply chain, ensuring that products are sourced, produced, and distributed in compliance with environmental and ethical standards (Queiroz et al., 2020). Blockchain enables end-to-end traceability by recording every transaction and movement of goods on a decentralized ledger. This allows companies to monitor the entire lifecycle of a product, from raw material extraction to the end consumer, ensuring that sustainability standards are maintained at every stage. Moreover, blockchain's decentralized nature mitigates the risk of fraud and tampering in supply chain operations. In traditional supply chains, information is often siloed and controlled by intermediaries, leading to opportunities for fraudulent activities and manipulation of records. Blockchain eliminates the need for intermediaries by enabling peer-to-peer transactions on a secure and transparent network (Abeyratne and Monfared, 2016). This reduces the risk of fraud and increases the trustworthiness of supply chain data, promoting more ethical and sustainable practices.

Sustainability has become a critical priority for businesses as they face mounting pressure from consumers, regulators, and investors to adopt more environmentally responsible practices. Blockchain technology has the potential to play a pivotal role in enabling businesses to meet their sustainability goals by enhancing the accountability and traceability of their supply chain operations (Saber et al., 2019). By providing a transparent and immutable record of all supply chain activities, blockchain can help businesses monitor their environmental impact, reduce waste, and ensure compliance with global sustainability standards. This, in turn, can enhance the reputation and competitiveness of businesses in an increasingly sustainability-conscious market (Ochigbo et al., 2024a).

Furthermore, blockchain can facilitate the integration of circular economy principles into supply chain management. The circular economy is a model that emphasizes reducing waste, reusing materials, and recycling products to minimize environmental impact (Kouhizadeh et al., 2019). Blockchain can support this model by providing a transparent record of material flows, enabling businesses to track the lifecycle of products and materials, and ensuring that they are reused or recycled in accordance with sustainability standards. This can help businesses reduce their environmental footprint and contribute to the transition towards a more sustainable and circular economy.

While the potential benefits of blockchain for supply chain sustainability are significant, its adoption is not without challenges, particularly for small and medium-sized enterprises (SMEs). SMEs often face barriers to technology adoption, including limited financial resources, lack of technical expertise, and concerns about scalability (Morkunas et al., 2019). Implementing blockchain in supply chains requires significant investment in technology infrastructure and personnel training, which can be prohibitively expensive for SMEs. Additionally, the complexity of blockchain technology and the need for collaboration with multiple stakeholders across the supply chain can pose challenges for smaller businesses (Saber et al., 2019).

Despite these challenges, the growing importance of sustainability and the increasing demand for transparency in supply chains make blockchain a critical tool for businesses looking to enhance their sustainability practices. For SMEs, blockchain adoption may require a strategic approach that involves collaboration with technology providers, industry partners, and regulators to overcome financial and technical barriers (Kouhizadeh and Sarkis, 2018). Governments and industry organizations can also play a role by providing financial incentives, technical support, and regulatory frameworks that promote the adoption of blockchain technology in supply chains, particularly for SMEs.

Blockchain technology offers significant potential to enhance transparency, traceability, and sustainability in supply chains across industries. Its ability to provide a secure, decentralized, and immutable record of transactions makes it an ideal solution for addressing the challenges of modern supply chain management, including fraud, inefficiencies, and lack of visibility. While the adoption of blockchain presents challenges for SMEs, particularly in terms of cost and scalability, strategic collaboration and support from governments and industry organizations can help overcome these barriers. As sustainability becomes an increasingly important priority for businesses and consumers, blockchain is poised to play a critical role in shaping the future of sustainable supply chains (Ochigbo et al., 2024b).

1.2. Objectives of the Review

Blockchain technology has garnered significant attention in recent years due to its potential to transform various sectors, particularly in supply chain management. As global supply chains become increasingly complex, they face numerous challenges related to sustainability, transparency, traceability, and accountability. Traditional supply chains are often marred by inefficiencies, fraudulent activities, and a lack of visibility across different stages, all of which contribute to sustainability concerns. Blockchain, as a distributed ledger technology, offers a decentralized and immutable method for recording transactions, providing an opportunity to address many of these persistent issues. The primary objective of this review is to analyze the role of blockchain technology in enhancing sustainability across supply chains, with a specific focus on its implementation by small and medium-sized enterprises (SMEs).

In light of the growing demand for transparency and accountability in supply chains, this review aims to explore how blockchain can help companies meet global sustainability standards while maintaining competitive advantage. Businesses are increasingly under pressure to ensure that their operations are environmentally responsible and ethically sound. These pressures come from regulatory bodies, consumers, and investors alike, who are demanding that companies adopt more sustainable practices. Blockchain technology has emerged as a viable solution to meet these expectations by offering a platform for transparent and traceable supply chain operations. This review seeks to examine the specific ways in which blockchain can be leveraged to improve the sustainability of supply chains, with particular attention paid to its potential for reducing inefficiencies, minimizing environmental impact, and ensuring compliance with sustainability regulations.

One of the core objectives of this review is to investigate the challenges and opportunities associated with blockchain adoption in supply chains, particularly for SMEs. While blockchain has been successfully implemented by large corporations, SMEs face unique challenges, including limited financial resources, technical expertise, and scalability issues. SMEs play a crucial role in the global economy and contribute significantly to various industries, including manufacturing, retail, and agriculture. Therefore, it is important to understand the barriers to blockchain adoption for these smaller businesses and explore strategies to overcome these obstacles. The review will examine case studies and real-world examples to identify best practices for implementing blockchain in SME supply chains and propose a framework tailored to the specific needs of SMEs.

Another objective of this review is to analyze the potential of blockchain to support circular economy principles in supply chain management. The circular economy is a model that promotes reducing waste, reusing materials, and recycling products in order to minimize environmental impact. As sustainability becomes a priority for businesses across industries, the integration of circular economy practices into supply chains is gaining traction. Blockchain can facilitate this transition by providing a transparent and immutable record of material flows, ensuring that products and

materials are reused or recycled by sustainability standards. This review will explore how blockchain can support the circular economy and how SMEs can benefit from adopting such practices.

Furthermore, this review aims to evaluate the potential risks and limitations of blockchain technology in supply chain management. While blockchain offers numerous benefits, its adoption is not without challenges. The technology is still in its infancy, and issues related to scalability, energy consumption, and regulatory uncertainty persist. For SMEs, these challenges are particularly pronounced, as they may lack the resources and expertise needed to implement blockchain solutions effectively. This review will assess the current limitations of blockchain technology and explore potential solutions to mitigate these risks, with a focus on providing practical recommendations for SMEs.

In addition to identifying challenges, this review also seeks to highlight the benefits that blockchain can bring to supply chain sustainability. Transparency and traceability are two of the most significant advantages that blockchain offers, allowing companies to track products from the sourcing of raw materials to the delivery of final goods. This level of visibility can help businesses ensure that their supply chains are sustainable and ethical, thereby enhancing their reputation and gaining the trust of consumers. By analyzing case studies and academic research, this review will demonstrate how blockchain can be a valuable tool for improving supply chain sustainability and provide a roadmap for SMEs looking to implement the technology.

The final objective of this review is to propose a framework for the successful implementation of blockchain in SME supply chains. Based on the analysis of challenges, opportunities, and best practices, this framework will provide a step-by-step guide for SMEs to adopt blockchain technology in a cost-effective and scalable manner. It will address key considerations such as initial investment, technology integration, stakeholder collaboration, and compliance with sustainability regulations. This framework is intended to serve as a practical tool for SMEs to leverage blockchain technology to enhance their sustainability practices and maintain competitive advantage in an increasingly sustainability-conscious market.

This review aims to provide a comprehensive analysis of the role of blockchain technology in promoting sustainable supply chains, with a particular focus on its implementation by SMEs. By examining the benefits, challenges, and opportunities associated with blockchain adoption, this review seeks to offer valuable insights for businesses looking to enhance their sustainability practices. The proposed framework will provide a roadmap for SMEs to overcome the barriers to blockchain adoption and leverage the technology to achieve their sustainability goals. As blockchain continues to evolve, it is poised to play a critical role in shaping the future of sustainable supply chain management across industries.

1.3. Clarification of the review's aims and scope, specifically focusing on the benefits of blockchain technology for sustainable supply chains and how SMEs can effectively implement it

Blockchain technology has emerged as a powerful tool with the potential to revolutionize supply chain management, particularly concerning sustainability. The increasing demand for transparency, traceability, and accountability in global supply chains has created an urgent need for solutions that can enhance the ethical and environmental standards of businesses. The decentralized, immutable nature of blockchain provides a unique opportunity to address these challenges, offering benefits that range from enhanced operational efficiency to the reduction of environmental footprints. The primary aim of this review is to clarify the benefits of blockchain technology in fostering sustainable supply chains, with a particular focus on small and medium-sized enterprises (SMEs). By exploring the potential for blockchain to improve sustainability practices, this review seeks to offer a comprehensive framework that SMEs can utilize to implement blockchain solutions effectively.

Sustainability has become a priority for businesses globally, driven by increasing consumer awareness, stricter regulatory standards, and the growing need to mitigate climate change. As businesses navigate these pressures, blockchain technology presents an opportunity to address key sustainability issues in supply chains. One of the most significant benefits of blockchain technology is its ability to increase transparency across supply chains. Traditional supply chains are often characterized by information asymmetry and inefficiencies, where stakeholders, including consumers, struggle to obtain reliable data on the origins of products and the ethical standards employed in their production. Blockchain, through its distributed ledger, allows all transactions and processes within the supply chain to be tracked and recorded immutably, providing stakeholders with access to real-time data that verifies the sustainability credentials of products. This transparency not only builds trust but also ensures that businesses are held accountable for their sustainability practices.

Another key benefit of blockchain technology for sustainable supply chains is traceability. The ability to track the journey of a product from raw material sourcing to final delivery is critical in ensuring that supply chains are environmentally responsible and compliant with ethical standards. Blockchain enables end-to-end traceability by providing an unalterable record of each transaction and movement within the supply chain. This capability is particularly valuable in industries where ensuring compliance with sustainability regulations is a major concern, such as agriculture, food production, and manufacturing. By leveraging blockchain, businesses can track and verify the sustainability of their supply chains, ensuring that raw materials are ethically sourced, production processes are environmentally friendly, and products are delivered to consumers with minimal impact on the environment.

For SMEs, the implementation of blockchain technology in supply chains offers both significant benefits and unique challenges. While larger corporations have already begun to adopt blockchain solutions, SMEs often face barriers such as limited financial resources, lack of technical expertise, and concerns about scalability. Despite these challenges, the potential benefits of blockchain for SMEs are profound. Blockchain can help SMEs streamline their operations by reducing inefficiencies and eliminating the need for intermediaries, thus reducing costs. Additionally, blockchain's ability to provide a secure and decentralized platform for peer-to-peer transactions offers SMEs a level playing field, allowing them to compete with larger companies that have traditionally dominated global supply chains.

The scope of this review includes an in-depth examination of how SMEs can effectively implement blockchain technology in their supply chains to enhance sustainability. SMEs play a critical role in the global economy, contributing significantly to various sectors, including manufacturing, retail, and agriculture. However, the lack of resources and technical expertise often makes it difficult for SMEs to adopt emerging technologies. This review will explore strategies that SMEs can use to overcome these barriers, including collaborations with technology providers, industry partnerships, and government initiatives that support technology adoption. By offering practical insights into the implementation of blockchain, this review seeks to provide SMEs with a clear roadmap for leveraging the technology to improve sustainability outcomes in their supply chains.

Moreover, this review will address the role of blockchain in supporting circular economy practices in supply chains. The circular economy emphasizes the importance of reducing waste, reusing materials, and recycling products to minimize environmental impact. Blockchain technology can facilitate this by providing an immutable record of material flows and ensuring that products are reused or recycled according to sustainability standards. For SMEs, adopting circular economy practices can offer significant cost savings and enhance their sustainability credentials, enabling them to compete more effectively in a market that increasingly prioritizes environmental responsibility. The review will explore how SMEs can use blockchain to integrate circular economy principles into their supply chains, offering a sustainable model for long-term business growth.

Finally, this review will clarify the risks and limitations associated with blockchain adoption in supply chains, particularly for SMEs. While the benefits of blockchain are well-documented, its adoption comes with certain challenges, including concerns about scalability, high energy consumption, and regulatory uncertainty. SMEs, in particular, may struggle to overcome these barriers due to their limited resources and technical capacity. This review will examine the current limitations of blockchain technology and propose solutions for mitigating these risks, with a focus on providing practical recommendations that are relevant to SMEs.

This review aims to provide a comprehensive analysis of the role of blockchain technology in enhancing sustainable supply chains, with a specific focus on SMEs. By examining the benefits, challenges, and opportunities associated with blockchain adoption, this review will offer valuable insights for businesses looking to improve their sustainability practices. Through a thorough examination of existing literature, case studies, and real-world examples, this review seeks to clarify how SMEs can effectively implement blockchain to enhance the sustainability of their supply chains, providing a roadmap for overcoming the barriers to adoption and maximizing the benefits of this transformative technology.

1.4. Current Challenges in Supply Chain Sustainability for SMEs: Discussion of the challenges SMEs face in achieving supply chain sustainability, such as limited resources, lack of transparency, and difficulties in managing suppliers' sustainability practices

Achieving supply chain sustainability is a critical goal for small and medium-sized enterprises (SMEs) in today's globalized market, where sustainability has become a major concern for consumers, regulators, and businesses alike. However, SMEs face several unique challenges in this regard, which hinder their ability to implement sustainable practices effectively. These challenges, which include limited financial resources, lack of transparency, and difficulties in managing the sustainability practices of their suppliers, present significant obstacles to achieving a fully sustainable

supply chain. The purpose of this review is to explore the specific challenges SMEs encounter in their pursuit of supply chain sustainability and to propose potential solutions for overcoming these barriers.

One of the most significant challenges SMEs face in striving for supply chain sustainability is their limited access to financial resources. Unlike large corporations that can allocate substantial budgets to sustainability initiatives, SMEs often operate under tight financial constraints, making it difficult for them to invest in the technologies and practices necessary to achieve sustainability. For instance, implementing advanced technologies such as blockchain for enhanced transparency or adopting more sustainable raw materials often requires considerable upfront investment, which may be beyond the reach of smaller enterprises (Morkunas et al., 2019). Moreover, many SMEs may struggle to justify these investments when faced with the immediate pressures of day-to-day business operations and profitability. This lack of financial capacity creates a significant barrier to the adoption of sustainable supply chain practices, which can lead to missed opportunities for SMEs to enhance their competitiveness and meet growing consumer demand for sustainability.

Another major challenge for SMEs in achieving supply chain sustainability is the lack of transparency across their supply chains. Supply chain transparency is essential for businesses to ensure that their products are sourced, produced, and distributed in compliance with environmental and ethical standards. However, many SMEs have limited visibility into their supply chains, particularly when working with suppliers in distant locations or multiple tiers of suppliers. This lack of visibility can make it difficult for SMEs to verify whether their suppliers are adhering to sustainability practices, such as responsible sourcing or minimizing environmental impact (Saberi et al., 2019). Additionally, the complexity of global supply chains, coupled with the limited technological capacity of many SMEs, exacerbates this challenge, making it harder for them to track and monitor their suppliers' operations effectively. Without proper transparency, SMEs may unintentionally engage in unsustainable practices, thereby damaging their reputation and exposing themselves to regulatory risks.

Managing the sustainability practices of suppliers is another key challenge for SMEs. Suppliers play a crucial role in determining the overall sustainability of a supply chain, as they are often responsible for sourcing raw materials, manufacturing products, and ensuring compliance with environmental standards. However, for many SMEs, managing supplier sustainability practices is a daunting task, particularly when working with suppliers in different regions or countries where sustainability regulations may vary (Kouhizadeh and Sarkis, 2018). SMEs often lack the bargaining power and resources needed to influence their suppliers' sustainability practices, and they may find it challenging to conduct thorough audits or monitor compliance. This can result in a situation where SMEs are reliant on suppliers who may not prioritize sustainability, leading to a disconnect between the SME's sustainability goals and the actual practices taking place within their supply chain. As a result, SMEs face increased risks of non-compliance with sustainability standards, which can have negative implications for their brand image and market position.

In addition to these financial, transparency, and supplier management challenges, SMEs often face difficulties in navigating the complex regulatory environment surrounding sustainability. Governments and international organizations are increasingly implementing regulations and standards aimed at promoting sustainability across industries, but keeping up with these evolving requirements can be particularly challenging for SMEs. Many smaller businesses lack the internal expertise or resources to stay informed about new regulations and may struggle to ensure compliance with environmental standards (Queiroz et al., 2020). Furthermore, the fragmented nature of sustainability regulations across different regions and industries can make compliance even more complex for SMEs that operate in global markets. As a result, SMEs may find themselves at a disadvantage when trying to implement sustainability initiatives that meet both local and international regulatory requirements.

Despite these challenges, achieving supply chain sustainability is increasingly important for SMEs in today's business environment. Consumers are becoming more conscious of the environmental and social impact of the products they buy, and they are demanding greater transparency from businesses regarding their sustainability practices. For SMEs, adopting sustainable supply chain practices can offer numerous benefits, including enhanced brand reputation, improved customer loyalty, and the ability to access new markets that prioritize sustainability. Moreover, as governments and international organizations continue to implement stricter sustainability regulations, SMEs that fail to adopt sustainable practices may face legal and financial penalties, as well as increased competition from more environmentally responsible businesses.

SMEs face a range of challenges in their pursuit of supply chain sustainability, including limited financial resources, lack of transparency, and difficulties in managing suppliers' sustainability practices. These challenges are further compounded by the complexity of navigating evolving sustainability regulations. However, despite these obstacles, the importance of sustainability in today's market cannot be overstated. For SMEs to remain competitive and compliant, they must develop strategies to overcome these challenges and integrate sustainability into their supply chain

operations. Solutions such as adopting advanced technologies like blockchain, collaborating with sustainability-focused partners, and staying informed about regulatory changes can help SMEs overcome the barriers they face and achieve long-term success in their sustainability efforts.

1.5. Overview of Methodological Approach: A brief overview of the methodological approach adopted for the systematic review, including data sourcing, search strategies, and criteria for study selection

This systematic review aims to analyze the potential of blockchain technology in enhancing sustainable supply chain management, with a particular focus on small and medium-sized enterprises (SMEs). To achieve this objective, a comprehensive and methodologically robust approach was adopted, ensuring that the review captured high-quality, relevant, and up-to-date research on the subject. The methodological approach employed involved several key stages, including data sourcing, search strategies, and the establishment of rigorous criteria for study selection.

The data sourcing for this review began with a systematic search of peer-reviewed academic journals, conference proceedings, and reputable industry reports. Major academic databases, such as ScienceDirect, Scopus, Web of Science, and Google Scholar, were utilized to ensure comprehensive coverage of the available literature. These databases were chosen because of their extensive repositories of high-quality research across various disciplines, including supply chain management, blockchain technology, and sustainability. Additionally, industry reports from organizations specializing in blockchain and supply chain innovations were included to provide practical insights and complement the academic literature.

The search strategies employed in this review were designed to maximize the retrieval of relevant studies while minimizing the inclusion of irrelevant or low-quality material. A combination of keywords and Boolean operators was used to structure the searches. The primary keywords included "blockchain," "supply chain sustainability," "sustainable supply chains," "SMEs," and "blockchain implementation." These keywords were selected based on their relevance to the research objectives and their prevalence in the existing literature on blockchain technology and sustainability. Boolean operators such as "AND" and "OR" were employed to refine the search results, ensuring that studies covering both blockchain and sustainability in supply chains were prioritized. For example, searches such as "blockchain AND supply chain sustainability" or "blockchain AND SMEs AND sustainable supply chains" were frequently used to narrow down the search to studies that focused on the intersection of these key areas.

To further ensure the robustness of the search strategy, inclusion and exclusion criteria were developed. The inclusion criteria focused on selecting studies that provided empirical data, theoretical frameworks, or case studies related to blockchain technology in the context of supply chain sustainability, particularly with relevance to SMEs. Studies that focused on large corporations without addressing SME-specific challenges or those that did not pertain to sustainability were excluded. Additionally, only studies published in English were included, given the accessibility constraints and the aim to review literature with broad international applicability. Studies published between 2015 and 2023 were prioritized, as the blockchain landscape has evolved significantly in recent years, and the review aimed to capture the most current advancements and applications of the technology.

Once the search results were obtained, a rigorous screening process was implemented. The screening involved two stages: title and abstract screening, followed by full-text screening. During the title and abstract screening phase, studies were reviewed to assess their relevance to the research questions based on their titles and abstracts. If a study appeared to be relevant, it was included in the full-text screening phase, where the entire paper was reviewed in detail. The purpose of this phase was to ensure that the selected studies not only addressed blockchain technology and supply chain sustainability but also provided substantial insights into their application within SMEs. Studies that lacked sufficient detail, depth, or empirical evidence were excluded at this stage.

To ensure that the selection process was as objective and unbiased as possible, two reviewers independently screened the studies. In cases where there were disagreements about the relevance of a study, a third reviewer was consulted to resolve the differences and reach a consensus. This double-blind screening process helped to enhance the reliability of the study selection and reduce the risk of bias in the review.

In terms of data extraction, a structured approach was followed to capture key information from each selected study. A data extraction form was developed to ensure consistency in the collection of relevant data points. The form included fields for the study's title, author(s), publication year, research objectives, methodology, key findings, and relevance to blockchain technology and supply chain sustainability. Special attention was given to studies that provided empirical data, case studies, or in-depth analyses of blockchain implementation in SMEs, as these were critical to understanding the practical challenges and opportunities associated with the technology's adoption.

After the data extraction process, the studies were analyzed and synthesized to identify key themes, patterns, and insights. Thematic analysis was employed to categorize the findings into major themes such as the benefits of blockchain technology for supply chain transparency, traceability, and sustainability, as well as the challenges SMEs face in adopting the technology. A critical assessment of each study's methodological rigor, strengths, and limitations was also conducted, ensuring that only high-quality studies informed the conclusions of the review. Furthermore, any gaps in the literature were identified, providing a foundation for future research directions.

This systematic review adopted a comprehensive and structured methodological approach to ensure the inclusion of high-quality, relevant studies on the potential of blockchain technology in enhancing sustainable supply chains for SMEs. By employing rigorous data sourcing techniques, carefully designed search strategies, and strict criteria for study selection, the review provides a robust analysis of the current state of knowledge in this field. The insights derived from the review offer valuable contributions to both academic research and practical applications, with the potential to inform future innovations in blockchain technology and sustainable supply chain management.

2. Literature Review

2.1. Overview of Blockchain Technology in Supply Chains: Exploration of the fundamental concepts of blockchain technology, including its decentralized nature, distributed ledgers, smart contracts, and how these features enhance supply chain operations

Blockchain technology has emerged as a transformative innovation across various industries, with supply chain management being one of the most notable areas experiencing its disruptive impact. The technology's decentralized nature, distributed ledger system, and smart contracts offer promising solutions to many of the challenges traditionally faced in global supply chains. By enhancing transparency, traceability, and efficiency, blockchain is redefining the operations of supply chains, addressing issues such as trust deficits, delayed processes, and inefficiencies.

At its core, blockchain technology operates on a decentralized network, where no single entity has control over the entire system. This decentralized nature fundamentally alters traditional supply chain models, which often rely on a centralized authority for oversight and control. Instead of a single intermediary overseeing transactions, blockchain enables peer-to-peer transactions verified by participants across the network. This peer-to-peer structure significantly reduces the likelihood of fraud and manipulation, as each participant has access to the same information. The decentralized approach of blockchain can help mitigate the issues associated with centralized models, such as the vulnerability to single points of failure, which can be disastrous in supply chain operations (Saber et al., 2019).

One of the most important elements of blockchain technology is the distributed ledger system. In this system, a shared and immutable ledger records all transactions across the network. Each transaction is recorded in blocks, which are then linked or "chained" together, ensuring the integrity and immutability of the data. Once data is entered into the blockchain, it cannot be altered without consensus from the network. This feature is particularly valuable in supply chain management, where accurate tracking of goods and materials across multiple stages is essential. The ability to provide an immutable record of the journey of goods from production to delivery enhances both traceability and accountability, making it easier for companies to verify the authenticity and origins of products (Kamilaris, Fonts & Prenafeta-Boldú, 2019). This not only helps companies ensure compliance with regulations but also builds trust among consumers who demand greater transparency about the products they purchase.

In addition to distributed ledgers, smart contracts represent another powerful feature of blockchain technology that has significant implications for supply chain management. Smart contracts are self-executing contracts where the terms of the agreement are directly written into lines of code. These contracts automatically enforce the agreed-upon terms once predefined conditions are met, eliminating the need for intermediaries such as lawyers or brokers. In a supply chain context, smart contracts can be used to automate various processes, such as payments or the release of goods. For instance, a smart contract could be programmed to release payment to a supplier as soon as the goods are delivered and verified by the blockchain. This automation not only reduces delays but also minimizes the potential for disputes, as the conditions for payment or delivery are clear and unalterable (Casino, Dasaklis & Patsakis, 2019).

The combination of decentralized systems distributed ledgers, and smart contracts creates a more efficient and secure supply chain. One of the most significant benefits is the increased level of transparency. Traditional supply chains often suffer from a lack of visibility, especially when they involve multiple stakeholders across different geographic locations. Blockchain's distributed ledger enables all participants to access the same real-time information, reducing the opacity that often leads to inefficiencies and mistrust. Furthermore, the immutability of blockchain records ensures that once

data is entered, it cannot be changed, which helps prevent fraud and errors that can disrupt supply chain operations (Francisco & Swanson, 2018).

Traceability is another critical enhancement brought about by blockchain in supply chains. By allowing every step in the supply chain to be recorded and traced on the blockchain, companies can track products from their origin to the final consumer. This is particularly valuable in industries where provenance is important, such as in the food, pharmaceutical, or luxury goods sectors. In the event of a product recall or safety issue, companies can quickly identify the source of the problem and take corrective action. Moreover, consumers are increasingly demanding transparency in product sourcing, and blockchain can provide them with verifiable proof of the origins and journey of the products they purchase (Kshetri, 2018).

In addition to enhancing transparency and traceability, blockchain also improves the overall efficiency of supply chains. Traditional supply chains often involve a significant amount of paperwork and manual processes, which can lead to delays and errors. By digitizing and automating many of these processes, blockchain reduces the need for intermediaries and manual intervention. Smart contracts, in particular, can automate key processes such as payments, customs clearance, and the transfer of goods, leading to faster transaction times and reduced costs. The reduced need for intermediaries also minimizes the chances of disputes, as the conditions of transactions are coded directly into the blockchain (Chang, Iakovou & Shi, 2020).

However, despite these benefits, the implementation of blockchain in supply chains is not without its challenges. One significant hurdle is the integration of blockchain technology with existing supply chain systems. Many companies have legacy systems that are not easily compatible with blockchain, requiring significant investment in new infrastructure. Additionally, there are concerns about the scalability of blockchain networks, especially when dealing with large volumes of transactions, as is typical in global supply chains. Moreover, while blockchain can provide transparency, it also raises issues related to data privacy, as all participants in the network have access to the same information. Balancing the need for transparency with the protection of sensitive data remains a challenge (Kouhizadeh, Saberi & Sarkis, 2021).

Blockchain technology offers a wide range of benefits for supply chain management, including increased transparency, traceability, and efficiency. Its decentralized nature, combined with distributed ledgers and smart contracts, provides a more secure and streamlined approach to managing complex supply chains. While challenges remain, particularly in terms of integration and scalability, the potential for blockchain to revolutionize supply chains is undeniable.

2.2. Blockchain for Supply Chain Transparency and Traceability: Analysis of how blockchain technology improves supply chain transparency and traceability, enabling better tracking of goods and services, reducing fraud, and improving sustainability reporting

Blockchain technology has rapidly gained prominence as a solution for enhancing supply chain transparency and traceability, addressing long-standing challenges such as tracking goods, reducing fraud, and improving sustainability reporting. Traditional supply chains, particularly those spanning multiple geographic regions and involving numerous intermediaries, have struggled with limited visibility and trust among participants. Blockchain, through its decentralized, immutable, and distributed ledger system, offers a robust framework to resolve these inefficiencies, making supply chains more transparent, reliable, and efficient (Ehimuan et al., 2024a).

One of the primary benefits of blockchain technology in supply chains is its ability to improve transparency. In conventional supply chains, the lack of shared data and the use of multiple siloed systems result in information asymmetries, where different participants possess differing or incomplete views of the data. Blockchain solves this issue by providing a single source of truth that is visible to all authorized participants. Every transaction or movement of goods is recorded on the blockchain and becomes immutable, creating a shared ledger that provides full visibility into the supply chain. This increased transparency enables companies to verify the authenticity and source of their products and services. For instance, Walmart has successfully used blockchain to track the origin of food products, ensuring safety and compliance with regulatory standards (Kamilaris, Fonts & Prenafeta-Boldú, 2019). The transparency offered by blockchain is especially important for industries such as food and pharmaceuticals, where the integrity of the supply chain has a direct impact on consumer health and safety.

Traceability is another critical improvement facilitated by blockchain. The ability to trace the entire journey of a product, from raw material to end consumer, has become increasingly important, particularly in the context of globalized supply chains. Traditional methods of tracking are often cumbersome, relying on paper-based systems or fragmented digital records that can be easily manipulated or lost. Blockchain, on the other hand, enables real-time, end-

to-end traceability by creating a permanent record of each transaction. This capability not only reduces the time required to track products but also ensures that the data cannot be tampered with. For instance, in the case of a product recall, blockchain can help identify the specific batch or supplier responsible for the defect, allowing companies to act quickly and minimize damage. This is particularly relevant in industries such as food and electronics, where product recalls can have significant financial and reputational repercussions (Kshetri, 2018).

Moreover, blockchain technology has the potential to significantly reduce fraud in supply chains. Fraudulent activities such as counterfeiting, mislabeling, and document forgery are prevalent issues in many industries, particularly in high-value goods sectors like luxury items and pharmaceuticals. Blockchain's immutable ledger provides an auditable trail that can be traced back to the origin of the product, making it extremely difficult for fraudulent actors to alter or falsify records. The transparent and tamper-proof nature of blockchain data ensures that all participants in the supply chain have access to the same information, which can be independently verified by third parties. This level of transparency and traceability not only deters fraudulent behavior but also strengthens trust among supply chain participants (Saberi et al., 2019).

In addition to improving transparency and reducing fraud, blockchain technology can enhance sustainability reporting within supply chains. Sustainability has become a key concern for both consumers and regulatory bodies, with increasing demands for companies to demonstrate their environmental and social responsibility. Blockchain can provide verifiable and immutable records of sustainability metrics, such as carbon emissions, labor conditions, and resource use, across the entire supply chain. By embedding sustainability data into the blockchain, companies can provide evidence of their adherence to sustainability standards and regulatory requirements. This can improve corporate accountability and enhance the credibility of sustainability reports, which are often criticized for their lack of transparency and verifiability (Chang, Iakovou & Shi, 2020). Furthermore, blockchain can be used to certify the authenticity of products marketed as sustainable or ethically sourced, helping to combat greenwashing and other deceptive marketing practices (Francisco & Swanson, 2018).

While blockchain offers many advantages for supply chain transparency, traceability, and fraud reduction, it is important to acknowledge the challenges that come with its implementation. One of the primary hurdles is the lack of interoperability between different blockchain platforms. Many supply chains operate across various industries and geographies, each with its specific systems and standards. For blockchain to be effective, there needs to be seamless integration with existing legacy systems, as well as standardization of blockchain protocols across industries. Additionally, the scalability of blockchain remains a challenge, particularly in supply chains that handle large volumes of transactions. Public blockchain networks, which are more decentralized, often suffer from slower transaction speeds and higher energy consumption, which may limit their applicability in high-volume supply chains. Private or permissioned blockchains offer a solution by increasing efficiency and control, but they may sacrifice some of the decentralization and transparency benefits inherent to blockchain technology (Kouhizadeh, Saberi & Sarkis, 2021).

Another consideration is the issue of data privacy. While blockchain's transparency is a key benefit for traceability and fraud prevention, it can also raise concerns about the exposure of sensitive business data. Companies may be hesitant to adopt blockchain if it means sharing proprietary information with competitors or exposing confidential transactions to the public (Ehimuan et al., 2024b). To address this, many blockchain platforms are developing privacy-enhancing features, such as zero-knowledge proofs and encryption, to ensure that sensitive data remains protected while still enabling transparency and traceability for regulatory and auditing purposes (Saberi et al., 2019).

Blockchain technology presents a compelling solution for improving transparency, traceability, and fraud reduction in supply chains. Its ability to provide an immutable, decentralized, and transparent ledger offers significant advantages over traditional methods of supply chain management. While there are challenges to overcome, such as interoperability, scalability, and data privacy, the potential benefits of blockchain for enhancing supply chain transparency and sustainability reporting are substantial. As technology matures, it is likely to become an integral part of global supply chain operations, helping companies meet the growing demand for trust, accountability, and sustainability in their operations.

2.3. Case Studies of Blockchain for Sustainable Supply Chains: Review of specific case studies where blockchain has been implemented to create more sustainable supply chains, emphasizing lessons learned and best practices, with a focus on applications relevant to SMEs.

Blockchain technology has emerged as a transformative solution for creating sustainable supply chains, particularly relevant to small and medium-sized enterprises (SMEs). Several case studies have demonstrated its potential to enhance transparency, traceability, and efficiency, thus addressing key sustainability challenges faced by global supply

chains. This literature review examines these case studies to extract valuable lessons and identify best practices that can inform the adoption of blockchain for SMEs, with a focus on environmental, social, and governance (ESG) outcomes.

One notable case study is that of Provenance, a UK-based company that has successfully implemented blockchain technology to improve the transparency of food supply chains. Provenance's blockchain platform allows consumers to track products from their source to the point of sale, ensuring the integrity of sustainability claims (Naiho et al., 2024a). This implementation has been particularly effective in the seafood industry, where traceability is critical to preventing illegal, unreported, and unregulated (IUU) fishing practices. By using blockchain to create an immutable record of each transaction, Provenance has helped companies comply with environmental standards, reducing their environmental impact (Kamilaris et al., 2019). SMEs in the food sector can benefit from this approach by providing consumers with greater confidence in the sustainability of their products, enhancing brand reputation and market share.

A similar application is seen in the fashion industry, where blockchain has been used to ensure the ethical sourcing of materials. A case study of the luxury fashion brand, Martine Jarlgaard, illustrates how blockchain can be leveraged to create a transparent supply chain that tracks the journey of garments from raw materials to finished products. By integrating blockchain into its operations, the company has ensured that consumers can verify the ethical sourcing of materials and the environmental impact of production processes (Saberli et al., 2019). This case highlights the potential for blockchain to not only improve transparency but also strengthen stakeholder trust, which is crucial for SMEs operating in industries with heightened scrutiny over environmental and social issues (Layode et al., 2024a).

In the automotive sector, blockchain has also demonstrated its utility in promoting sustainability. A case study of the Renault blockchain project shows how the technology can be applied to improve the traceability of vehicle parts. By embedding blockchain in its supply chain, Renault created a comprehensive, immutable record of vehicle parts from production to end-of-life. This initiative has enhanced the company's ability to manage recalls and reduce waste, contributing to the circular economy. While the project was implemented on a large scale, the lessons learned can be applied by SMEs, particularly those seeking to improve product lifecycle management and align their operations with circular economy principles.

Blockchain's potential to facilitate sustainability is not limited to environmental concerns. In the coffee industry, Bext360 has employed blockchain technology to promote fair trade and social equity. By using blockchain to track the journey of coffee from farms to consumers, Bext360 ensures that farmers receive fair compensation for their products. The system allows all stakeholders in the supply chain to view transactions transparently, fostering trust and fairness (Wang et al., 2020). For SMEs, especially those in developing economies, adopting blockchain could serve as a critical tool in ensuring that social sustainability is achieved by maintaining fair labor practices and ethical sourcing (Layode et al., 2024b).

Beyond these industry-specific examples, several overarching lessons emerge from the implementation of blockchain for sustainable supply chains. First, the immutable nature of blockchain records ensures that all transactions are transparent and verifiable, which significantly enhances the accountability of supply chain actors. This characteristic is particularly beneficial for SMEs, as it mitigates the risk of fraud and misrepresentation, enabling them to establish trust with consumers and partners. Second, blockchain enables real-time data sharing across all supply chain participants, which facilitates better decision-making and quicker response times in addressing supply chain disruptions (Kouhizadeh et al., 2021). This capability is especially important for SMEs, which may lack the resources to manually manage complex supply chain logistics and compliance requirements.

However, the adoption of blockchain by SMEs also presents challenges. The cost of implementing blockchain infrastructure and the technical expertise required to manage the technology can be prohibitive for smaller firms. Nonetheless, these challenges are not insurmountable. A common best practice identified in several case studies is the collaboration with blockchain-as-a-service (BaaS) providers, which offer scalable solutions that reduce the financial and technical burdens on SMEs (Dolgui et al., 2020). By outsourcing blockchain development and maintenance to specialized providers, SMEs can leverage the benefits of blockchain without incurring the full cost of in-house development (Layode et al., 2024c).

The case studies reviewed demonstrate that blockchain technology holds significant promise for enhancing the sustainability of supply chains across various industries. From improving traceability and transparency to fostering social equity, blockchain has proven to be a valuable tool for addressing the sustainability challenges faced by SMEs. The lessons learned from these implementations underscore the importance of leveraging blockchain to build trust, enhance accountability, and streamline operations. However, SMEs must carefully consider the costs and technical demands associated with blockchain adoption, exploring collaborative solutions that can mitigate these challenges. As

blockchain technology continues to evolve, it is expected to play an increasingly central role in the development of sustainable supply chains, offering SMEs a pathway to achieve both environmental and social objectives.

2.4. Benefits of Blockchain for SMEs in Sustainable Supply Chains: Examination of how blockchain technology benefits SMEs by reducing operational costs, improving supplier collaboration, and fostering trust in supply chain transactions

Blockchain technology has gained significant attention for its potential to transform the operations of small and medium-sized enterprises (SMEs) by enhancing the transparency, security, and efficiency of sustainable supply chains. SMEs, which often face resource constraints and operational inefficiencies, can greatly benefit from blockchain implementation. Key advantages include reducing operational costs, improving supplier collaboration, and fostering trust in supply chain transactions. These benefits are critical to ensuring the competitiveness of SMEs in global markets, particularly in industries where sustainability and ethical supply chain practices are increasingly demanded by consumers and regulatory bodies. (Ajayi-Nifise, A.O., et al, 2024).

One of the most evident benefits of blockchain technology for SMEs in sustainable supply chains is its ability to reduce operational costs. Blockchain eliminates intermediaries and reduces the need for manual data entry and verification processes, leading to significant cost savings. Traditionally, SMEs have relied on complex, time-consuming processes to manage and verify transactions within their supply chains, often incurring additional costs due to inefficiencies. Blockchain simplifies these processes by automating transaction verification and ensuring that all parties involved in the supply chain have access to a shared, immutable ledger (Wamba et al., 2020). This not only streamlines operations but also reduces administrative costs associated with record-keeping and auditing. A notable example is the implementation of blockchain by logistics SMEs to track shipments, where the technology significantly reduced the costs associated with tracking and tracing goods throughout the supply chain (Saber et al., 2019). The elimination of intermediaries such as third-party verification agents further decreases transaction costs, making blockchain an attractive solution for resource-constrained SMEs (Naiho et al., 2024b).

In addition to cost reduction, blockchain enhances collaboration among suppliers in a supply chain, which is particularly beneficial for SMEs. Supplier collaboration is essential in creating a transparent and efficient supply chain, and blockchain facilitates this by providing all stakeholders with real-time access to data on the movement of goods, inventory levels, and compliance with sustainability standards. Blockchain's decentralized structure ensures that no single party has control over the data, promoting trust and cooperation between suppliers, manufacturers, and other participants (Kouhizadeh et al., 2021). This transparency enables SMEs to coordinate more effectively with their suppliers, ensuring that products are sourced sustainably and that potential disruptions in the supply chain are identified and resolved quickly. For example, in the agricultural sector, SMEs have used blockchain to collaborate with suppliers on the certification of organic products, ensuring that all participants in the supply chain comply with environmental and sustainability standards (Kamilaris et al., 2019). This collaborative approach enhances the overall efficiency of the supply chain and enables SMEs to compete with larger enterprises that have traditionally dominated the market due to their superior supply chain management capabilities (Tuboalabo et al., 2024a).

Blockchain technology also fosters trust in supply chain transactions, which is a critical challenge for SMEs operating in global supply chains. Trust is essential for the smooth functioning of any supply chain, but it is particularly important for SMEs that often lack the brand recognition and financial resources of larger companies. Blockchain addresses this challenge by providing a transparent and immutable record of all transactions, which is accessible to all participants in the supply chain. This transparency reduces the risk of fraud, counterfeiting, and unethical practices, thus fostering trust between SMEs, their suppliers, and consumers (Saber et al., 2019). In industries such as food and fashion, where consumers are increasingly concerned about the provenance and ethical sourcing of products, blockchain allows SMEs to provide verifiable proof of their sustainability claims, thereby building trust with customers. For instance, Provenance, a blockchain platform, enables SMEs to verify and communicate the origin of raw materials, ensuring that they meet sustainability and ethical sourcing standards (Kouhizadeh et al., 2021). By fostering trust in supply chain transactions, blockchain enhances the competitiveness of SMEs in markets where consumer confidence is a key driver of success.

While the benefits of blockchain for SMEs in sustainable supply chains are clear, there are also challenges associated with the adoption of the technology. One of the primary obstacles is the cost and expertise required for implementing blockchain solutions. SMEs often lack the technical skills and financial resources necessary to adopt blockchain at scale. However, partnerships with blockchain solution providers and participation in blockchain consortia have proven to be effective strategies for overcoming these barriers (Wamba et al., 2020). Additionally, blockchain's ability to automate compliance with regulatory and sustainability standards further reduces the burden on SMEs, allowing them to focus

on their core business activities while ensuring that they meet the growing demand for sustainable supply chain practices (Tuboalabo et al., 2024b).

Blockchain technology offers significant benefits to SMEs in sustainable supply chains by reducing operational costs, improving supplier collaboration, and fostering trust in transactions. These advantages position blockchain as a transformative tool for enhancing the competitiveness and sustainability of SMEs in global markets (Seyi-Lande et al., 2024). However, for widespread adoption, SMEs must overcome the challenges related to the cost and technical complexity of blockchain implementation. As more SMEs embrace blockchain, the lessons learned from early adopters will play a crucial role in ensuring the successful integration of the technology into sustainable supply chain practices.

3. Challenges and Strategic Solutions

3.1. Implementation Challenges for SMEs: Identification of the challenges SMEs face when implementing blockchain, such as high costs, technical complexity, integration with existing systems, and the need for skilled personnel

Blockchain technology offers significant potential for transforming supply chain operations, particularly in terms of transparency, traceability, and efficiency. However, small and medium-sized enterprises (SMEs) face several challenges in the implementation of blockchain solutions. These challenges, which include high costs, technical complexity, integration with existing systems, and the need for skilled personnel, can inhibit the adoption of blockchain technologies in SMEs, which often have limited resources and expertise.

One of the foremost challenges for SMEs when implementing blockchain technology is the high cost of deployment and maintenance. Blockchain infrastructure can be expensive, particularly in terms of initial setup, transaction fees, and ongoing operational costs. SMEs, which typically operate on tighter budgets compared to larger enterprises, may struggle to afford these costs. According to Agbo, Mahmoud, and Eklund (2019), the cost of implementing a blockchain system can be prohibitive, especially when considering the need for customisation to fit the specific needs of the supply chain. SMEs often lack the financial capacity to invest in these advanced technologies, making cost one of the most significant barriers to entry. In addition, operational costs associated with maintaining a blockchain network, such as energy consumption for proof-of-work mechanisms and the need for ongoing technical support, can further strain SMEs' financial resources (Saber et al., 2019). Therefore, while the potential benefits of blockchain are clear, its high costs often make it an unattainable solution for many SMEs.

Another critical challenge for SMEs is the technical complexity associated with blockchain systems. Blockchain technology, particularly in its more sophisticated forms, requires an in-depth understanding of cryptographic principles, consensus mechanisms, and network architecture. SMEs, which typically lack dedicated IT departments or in-house blockchain expertise, may find it difficult to navigate the technical intricacies involved in implementing blockchain solutions (Casino, Dasaklis, & Patsakis, 2019). The technical complexity of blockchain extends beyond basic installation to include the management of smart contracts, ensuring data integrity, and troubleshooting issues related to network performance and scalability. As highlighted by Mohanta, Panda, and Jena (2020), the complexity of blockchain architecture can create operational hurdles for SMEs, which may not have the internal expertise required to effectively manage and optimise blockchain systems. Consequently, many SMEs may need to rely on external consultants or third-party vendors, adding to the overall cost and further complicating the implementation process (Buinwi & Buinwi, 2024a).

Integration with existing systems represents another significant challenge for SMEs. Many SMEs already use legacy systems that are not designed to be compatible with blockchain technology. The process of integrating blockchain with existing enterprise resource planning (ERP) systems, databases, and supply chain management tools can be both time-consuming and costly. According to Kouhizadeh, Saber, and Sarkis (2021), legacy systems often require extensive re-engineering to ensure compatibility with blockchain technologies, and the lack of standardisation in blockchain platforms can exacerbate these integration challenges. SMEs may also face difficulties in ensuring that their blockchain solution can interoperate with the systems of supply chain partners, particularly if those partners use different technologies or platforms. This lack of standardisation and interoperability can hinder the smooth adoption of blockchain across supply chains, creating inefficiencies and reducing the effectiveness of blockchain implementation in addressing supply chain issues.

A further challenge for SMEs is the scarcity of skilled personnel with the expertise needed to manage blockchain technologies. Blockchain technology requires specialised skills in areas such as cryptography, programming, and data analysis, which are often beyond the reach of SMEs, particularly those in developing markets where access to advanced

technical training may be limited. The demand for blockchain expertise has grown significantly in recent years, creating a competitive job market that favours large corporations with the resources to attract top talent (Singh & Singh, 2019). SMEs, in contrast, often struggle to attract and retain employees with the necessary technical skills to develop and maintain blockchain solutions. This shortage of skilled personnel can slow the implementation process, increase reliance on external vendors, and potentially limit the effectiveness of blockchain technology once it is deployed. Moreover, even when SMEs can hire blockchain experts, the ongoing need for training and upskilling, as blockchain technology evolves, can pose additional challenges (Buinwi & Buinwi, 2024b).

To address these challenges, SMEs can adopt strategic solutions aimed at minimising the barriers to blockchain implementation. One such solution is the use of blockchain-as-a-service (BaaS) platforms, which offer a cost-effective and scalable way for SMEs to adopt blockchain technologies without the need for significant upfront investment in infrastructure. BaaS providers such as IBM, Microsoft, and Amazon Web Services offer SMEs access to blockchain technology through a subscription-based model, allowing them to focus on business operations while outsourcing the technical aspects of blockchain management (Casino, Dasaklis, & Patsakis, 2019). This approach can help SMEs to reduce costs and overcome the technical complexity of blockchain implementation.

In addition, SMEs can form partnerships with technology providers, universities, and industry associations to access the expertise and resources needed to implement blockchain solutions. These partnerships can provide SMEs with access to the technical knowledge and skills required to navigate the complexities of blockchain, while also fostering innovation through collaboration. According to Mohanta, Panda, and Jena (2018), collaboration with external stakeholders can help SMEs to bridge the knowledge gap and facilitate the integration of blockchain with existing systems.

Moreover, adopting open-source blockchain platforms can help SMEs to overcome integration challenges. Open-source platforms, such as Hyperledger and Ethereum, offer greater flexibility in terms of customisation and interoperability, allowing SMEs to tailor blockchain solutions to fit their existing systems (Saber et al., 2019). These platforms also benefit from large developer communities, which can provide SMEs with the technical support needed to address integration issues and ensure that their blockchain solutions remain scalable and secure.

While SMEs face several challenges in implementing blockchain technology, including high costs, technical complexity, integration issues, and the need for skilled personnel, strategic solutions such as BaaS platforms, partnerships, and open-source technologies can help to mitigate these barriers. By adopting these solutions, SMEs can unlock the potential of blockchain to transform their supply chains and gain a competitive advantage in the digital economy.

3.2. Strategic Solutions for Overcoming Blockchain Adoption Barriers: Insights into strategies for overcoming blockchain adoption barriers, including collaborations with technology providers, government incentives, blockchain-as-a-service platforms, and phased implementation approaches

Blockchain adoption presents significant potential for enhancing transparency, efficiency, and security in supply chain management and other business processes. However, small and medium-sized enterprises (SMEs) often face several challenges in implementing blockchain technology. Strategic solutions are essential to overcoming these barriers, enabling SMEs to harness the benefits of blockchain without being impeded by the associated complexities. Collaborations with technology providers, government incentives, blockchain-as-a-service (BaaS) platforms, and phased implementation approaches are some of the most effective strategies that SMEs can adopt to mitigate these challenges.

One of the most effective strategic solutions for SMEs seeking to adopt blockchain is to collaborate with technology providers. Technology providers, such as IBM and Microsoft, have developed blockchain platforms and services specifically designed to help businesses implement blockchain solutions without having to invest in significant infrastructure. According to Saber et al. (2019), collaborating with technology providers allows SMEs to access the technical expertise and resources required for blockchain deployment, reducing the financial and technical burdens typically associated with adoption. These partnerships can also facilitate knowledge transfer, helping SMEs to build in-house capacity over time. The role of technology providers is especially important in providing tailored solutions that align with the specific needs of SMEs, ensuring that blockchain implementation is both feasible and effective within the context of their existing operations (Morkunas, Paschen, & Boon, 2019).

Government incentives also play a pivotal role in encouraging SMEs to adopt blockchain technologies. In many cases, the high costs associated with blockchain implementation can deter SMEs from pursuing adoption. To address this, governments in various countries have introduced policies and programs aimed at subsidising the cost of blockchain

technology for SMEs. These incentives can take the form of tax breaks, grants, or low-interest loans designed to alleviate the financial burden on businesses. For instance, governments in regions such as the European Union have introduced blockchain-specific funding initiatives aimed at promoting innovation and supporting SMEs in adopting advanced technologies (Casino, Dasaklis, & Patsakis, 2019). Furthermore, government-led blockchain initiatives can help to foster a regulatory environment that promotes blockchain innovation while protecting businesses from the legal uncertainties that often accompany new technologies (Nembe, J.K, et al, 2024). By reducing the financial barriers and creating a supportive regulatory framework, government incentives can significantly accelerate the adoption of blockchain by SMEs.

Blockchain-as-a-service (BaaS) platforms provide another strategic solution for SMEs. BaaS platforms, such as those offered by Amazon Web Services (AWS) and Microsoft Azure, allow SMEs to leverage blockchain technology without the need for substantial upfront investments in infrastructure. Instead, SMEs can access blockchain networks and tools on a subscription basis, paying only for the services they use. This approach offers a cost-effective solution for SMEs, allowing them to experiment with blockchain technology and scale their usage as needed (Morkunas, Paschen, & Boon, 2019). BaaS platforms also remove the need for SMEs to manage complex technical aspects of blockchain, such as network maintenance and security. By outsourcing these functions to the BaaS provider, SMEs can focus on integrating blockchain into their business processes and unlocking its potential benefits. The use of BaaS platforms, therefore, not only reduces the financial and technical barriers to blockchain adoption but also provides SMEs with the flexibility to scale their blockchain operations in line with their growth and operational needs (Casino, Dasaklis, & Patsakis, 2019).

Phased implementation approaches are also critical to overcoming blockchain adoption barriers. Implementing blockchain in incremental stages allows SMEs to address challenges progressively, reducing the risk of disruption to business operations. Rather than attempting to implement blockchain across all areas of their supply chain or business processes at once, SMEs can focus on specific areas where blockchain is likely to deliver the greatest immediate value. This approach can help SMEs learn from early implementation experiences and refine their blockchain strategy over time. According to Kouhizadeh, Saberi, and Sarkis (2021), phased implementation allows businesses to gradually build the internal expertise and infrastructure needed to manage blockchain systems effectively. It also enables SMEs to pilot blockchain applications in low-risk environments before committing to full-scale implementation. This incremental approach can mitigate the financial and operational risks associated with blockchain adoption, making it a more feasible option for SMEs with limited resources (Agbo, Mahmoud, & Eklund, 2019).

Additionally, phased implementation provides an opportunity for SMEs to assess the scalability and interoperability of blockchain solutions. Many SMEs operate within supply chains that rely on collaboration with multiple stakeholders, each of which may use different technologies and platforms. The phased implementation allows SMEs to test the interoperability of their blockchain solution with the systems used by their supply chain partners. This can help to identify potential integration challenges early on and develop strategies for addressing these issues (Saberi et al., 2019). By taking a phased approach, SMEs can ensure that their blockchain implementation is both scalable and compatible with the broader supply chain ecosystem, enhancing the overall effectiveness of the technology.

The adoption of blockchain technology by SMEs is hindered by a range of challenges, including high costs, technical complexity, and integration difficulties. However, strategic solutions such as collaborations with technology providers, government incentives, BaaS platforms, and phased implementation approaches can help to overcome these barriers. These solutions enable SMEs to access the expertise, resources, and support they need to implement blockchain technologies effectively, without being overwhelmed by the associated financial or technical challenges. By adopting these strategies, SMEs can unlock the potential of blockchain to drive innovation, enhance efficiency, and improve their competitiveness in the digital economy.

4. Future Directions

4.1. Emerging Trends in Blockchain for Sustainable Supply Chains: Speculation on future trends, such as the integration of blockchain with the Internet of Things (IoT), artificial intelligence, and advanced analytics for enhanced sustainability in supply chains

The future of blockchain technology in sustainable supply chains promises to be transformative, driven by its integration with emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), and advanced analytics. These advancements are poised to reshape supply chain operations, significantly improving transparency, traceability, and sustainability. As blockchain continues to evolve, the convergence with IoT, AI, and advanced analytics will offer unprecedented opportunities for enhancing the efficiency and sustainability of global supply chains.

One of the most significant future trends in blockchain for sustainable supply chains is its integration with IoT. IoT devices can collect and transmit real-time data across the supply chain, allowing businesses to track the movement of goods, monitor environmental conditions, and measure energy usage at each stage of the process. By combining IoT with blockchain, this data can be stored in a decentralized and immutable ledger, ensuring the accuracy and reliability of the information. IoT-enabled blockchain solutions can enhance the traceability of products by providing real-time data on their origin, transportation, and storage conditions. This level of visibility is particularly crucial in sectors such as food and pharmaceuticals, where ensuring the authenticity and quality of products is essential for sustainability and consumer safety. Moreover, the integration of IoT and blockchain can help reduce waste in supply chains by allowing businesses to optimize inventory management and reduce overproduction.

Another emerging trend is the use of artificial intelligence in conjunction with blockchain to drive sustainability in supply chains. AI has the potential to enhance decision-making processes by analyzing the vast amounts of data generated by blockchain and IoT systems. By applying machine learning algorithms, businesses can predict supply chain disruptions, optimize logistics, and identify inefficiencies that contribute to environmental degradation. AI-powered blockchain solutions can also help automate complex processes such as demand forecasting, route optimization, and resource allocation, further improving the efficiency and sustainability of supply chains. (Adama, H.E. and Okeke, C.D., 2024). AI and blockchain together can enable more intelligent and adaptive supply chains, capable of responding to changing environmental conditions and market demands. This integration will not only improve operational efficiency but also contribute to achieving sustainability goals by minimizing resource consumption and reducing the carbon footprint of supply chains. (Addy, W.A., et al, 2024).

Advanced analytics is also expected to play a critical role in the future of blockchain-enabled sustainable supply chains. With the increasing availability of data from IoT devices and blockchain networks, advanced analytics tools can provide valuable insights into supply chain performance and sustainability. These tools can analyze data on energy usage, carbon emissions, and waste generation, enabling businesses to measure their environmental impact and identify opportunities for improvement. Advanced analytics can help businesses set sustainability targets and track their progress in real-time, allowing for more informed decision-making and greater accountability. By combining blockchain with advanced analytics, businesses can ensure that their sustainability efforts are transparent and verifiable, meeting the growing demand from consumers and regulators for sustainable practices.

The convergence of blockchain with IoT, AI, and advanced analytics is likely to drive innovation in sustainable supply chain management, particularly in the development of new business models and value-creation strategies. For example, blockchain-enabled circular supply chains, in which products are designed to be reused, repaired, or recycled, could become more prevalent in the future. By leveraging IoT and AI, businesses can track the lifecycle of products and materials, ensuring that they are returned to the supply chain at the end of their useful life. This approach not only reduces waste but also creates new revenue streams for businesses by enabling the efficient reuse of resources. Blockchain can provide the necessary transparency and traceability to support circular supply chains, ensuring that all stakeholders have access to accurate information on the provenance and condition of products.

As these trends continue to unfold, blockchain's role in promoting sustainability in supply chains is likely to expand, with increasing emphasis on collaboration and interoperability. Blockchain's ability to provide a decentralized and secure platform for data sharing makes it an ideal tool for fostering collaboration between supply chain partners. By enabling seamless data exchange, blockchain can help businesses work together to achieve common sustainability goals, such as reducing carbon emissions or minimizing resource consumption. The interoperability of blockchain networks will also be critical in ensuring that supply chain data can be shared across different platforms and systems, allowing for greater coordination and collaboration. This collaborative approach to blockchain adoption will be essential in addressing the complex and interconnected challenges of sustainability in global supply chains.

The future of blockchain in sustainable supply chains is characterized by its integration with IoT, AI, and advanced analytics, offering new opportunities for enhancing efficiency, transparency, and sustainability. These emerging technologies will enable businesses to monitor and optimize their supply chain operations in real-time, reducing waste and environmental impact. Furthermore, the convergence of blockchain with these technologies will drive the development of new business models, such as circular supply chains, that promote sustainability and resource efficiency. As blockchain technology continues to evolve, its role in shaping the future of sustainable supply chains will only become more significant, contributing to the achievement of global sustainability goals and the creation of more resilient and efficient supply chain networks.

4.2. Opportunities for SMEs in Blockchain-Driven Supply Chain Innovation: Exploration of opportunities for SMEs to capitalize on blockchain innovations, including building partnerships with larger firms, entering new markets, and leading in niche sustainable supply chain practices

Blockchain technology offers small and medium-sized enterprises (SMEs) considerable opportunities to innovate and enhance their supply chain operations. By leveraging blockchain-driven solutions, SMEs can improve transparency, traceability, and sustainability, allowing them to build strategic partnerships, enter new markets, and lead niche practices within sustainable supply chain management. Despite the technical and financial barriers that may impede blockchain adoption, the technology presents a unique set of benefits for SMEs willing to embrace its transformative potential.

One key opportunity for SMEs is the ability to build strategic partnerships with larger firms. Blockchain technology enables more transparent and efficient data sharing across supply chains, creating new avenues for collaboration between smaller enterprises and larger corporations. Through blockchain, SMEs can provide real-time data on the origin, quality, and sustainability of their products, making them attractive partners for larger firms that are increasingly focused on meeting environmental, social, and governance (ESG) criteria (Ikegwu, C.G., 2022). Large corporations are under growing pressure from stakeholders to demonstrate the sustainability of their supply chains, and SMEs that can offer blockchain-enabled transparency and traceability stand to gain a competitive advantage. By providing verifiable data on product origins, resource use, and emissions, SMEs can establish themselves as trusted partners in global supply chains, enabling them to build long-term relationships with larger firms.

In addition to fostering partnerships, blockchain technology also presents SMEs with the opportunity to enter new markets. Blockchain's ability to enhance supply chain visibility and accountability can be particularly beneficial for SMEs operating in industries such as food and agriculture, pharmaceuticals, and textiles, where traceability is a critical concern. Consumers are increasingly demanding transparency in the products they purchase, especially when it comes to ethical sourcing, environmental impact, and fair labor practices. SMEs that adopt blockchain to provide transparent supply chain information can differentiate themselves in the marketplace, catering to the growing demand for ethically sourced and sustainable products. (Uzougbo, N.S., et al, 2024). By utilizing blockchain to enhance their value proposition, SMEs can not only improve customer trust but also gain access to international markets where sustainability is a key purchasing criterion.

Moreover, SMEs have the potential to lead in niche sustainable supply chain practices by leveraging blockchain technology to address specific environmental and social challenges. Blockchain can enable SMEs to pioneer innovative practices in areas such as circular economy, waste reduction, and resource efficiency. For instance, SMEs can use blockchain to track the lifecycle of materials and products, ensuring that they are recycled or reused rather than disposed of. Blockchain-driven circular supply chains offer SMEs a unique opportunity to create closed-loop systems, where products are designed with reuse and recycling in mind. By adopting such practices, SMEs can position themselves as leaders in sustainability, setting them apart from competitors and attracting eco-conscious customers and investors.

Another significant opportunity for SMEs lies in the automation and streamlining of supply chain processes through blockchain technology. Blockchain's ability to provide immutable and transparent records of transactions can reduce the need for intermediaries, streamline paperwork, and lower transaction costs. This is especially important for SMEs, which often face resource constraints and operational inefficiencies. By automating processes such as contract management, payments, and regulatory compliance, SMEs can reduce operational overheads and improve supply chain efficiency. Blockchain's smart contract functionality allows for the automation of agreements and payments, reducing the time and costs associated with manual contract enforcement and verification. For SMEs, this can lead to faster, more efficient supply chains, improving their competitiveness in both domestic and international markets. (Adama, H.E., et al, 2024).

The adoption of blockchain technology also provides SMEs with greater access to financing opportunities. Blockchain can facilitate supply chain finance by providing lenders with verifiable information on the financial health and operational performance of SMEs. With blockchain, financial institutions can assess risk more accurately, offering financing solutions that are better tailored to the needs of SMEs. Blockchain's ability to provide transparent, real-time data on the flow of goods and payments within supply chains reduces the risk for lenders, enabling them to offer more favorable financing terms to SMEs. This enhanced access to finance can help SMEs to grow and expand their operations, enabling them to scale their blockchain-driven supply chain innovations.

In the future, SMEs are likely to benefit from government support and incentives aimed at encouraging the adoption of blockchain technology in supply chains. Many governments are recognizing the role that blockchain can play in enhancing supply chain sustainability and are introducing policies to support its adoption. These include tax incentives, grants, and regulatory frameworks designed to reduce the cost and complexity of implementing blockchain. By capitalizing on these government incentives, SMEs can overcome the financial barriers associated with blockchain adoption and gain a competitive edge in sustainable supply chain practices.

Blockchain technology offers SMEs numerous opportunities to capitalize on supply chain innovations. By building partnerships with larger firms, entering new markets, and leading in niche sustainable practices, SMEs can leverage blockchain to enhance their competitiveness and improve their sustainability credentials. The ability to automate processes, access financing, and take advantage of government incentives further strengthens the business case for blockchain adoption by SMEs. While challenges such as high costs and technical complexity remain, the long-term benefits of blockchain for SMEs far outweigh these obstacles, positioning blockchain as a key driver of innovation and growth in the future of sustainable supply chain management.

5. Conclusion

Blockchain technology presents transformative potential for small and medium-sized enterprises (SMEs) seeking to enhance the transparency, traceability, and sustainability of their supply chains. Throughout this exploration of blockchain-driven supply chain innovations, several key findings have emerged that highlight the strategic opportunities available to SMEs. Despite the challenges associated with blockchain adoption, including financial and technical barriers, SMEs can position themselves at the forefront of supply chain innovation by adopting strategic approaches such as building partnerships with larger firms, entering new markets, and leading in niche sustainable practices.

One of the central findings is that blockchain technology offers SMEs a powerful tool to foster strategic partnerships with larger corporations. In a business environment increasingly driven by environmental, social, and governance (ESG) requirements, SMEs that can demonstrate blockchain-enabled transparency and traceability of their products are likely to gain a competitive advantage. Larger corporations are under pressure to ensure that their supply chains are sustainable and ethical, and SMEs that can provide real-time, verifiable data about their products' origins, resource usage, and emissions are well-positioned to collaborate with these firms. This collaboration not only strengthens SMEs' standing in the marketplace but also enhances their ability to scale their operations.

Another important finding is the opportunity for SMEs to access new markets through blockchain adoption. With growing consumer demand for ethical sourcing and sustainability, blockchain technology can provide the necessary transparency to appeal to consumers who prioritize these factors in their purchasing decisions. This trend is especially relevant in industries such as agriculture, textiles, and pharmaceuticals, where product authenticity and safety are paramount. By providing a clear and verifiable record of their supply chains, SMEs can differentiate themselves from competitors, build consumer trust, and access international markets where sustainability is becoming a key purchasing criterion.

The analysis also revealed that blockchain technology enables SMEs to take the lead in niche sustainable supply chain practices. By adopting blockchain-driven circular supply chains, for instance, SMEs can track the lifecycle of materials and products, ensuring that they are reused or recycled rather than discarded. This aligns with global movements toward reducing waste and promoting a circular economy. SMEs in regions like West Africa, where there is an increasing focus on sustainable resource management, can capitalize on this trend by offering solutions that reduce environmental impact and attract eco-conscious investors.

The potential for blockchain to automate and streamline supply chain processes is another key finding. For resource-constrained SMEs, reducing operational inefficiencies is critical to maintaining competitiveness. Blockchain technology offers the ability to automate processes such as contract management, payments, and regulatory compliance through the use of smart contracts. This can reduce transaction costs and paperwork, allowing SMEs to focus on core business activities and improve supply chain efficiency. In the Nigerian market, where SMEs play a significant role in the economy but often face challenges related to bureaucracy and inefficiency, blockchain offers a viable solution to enhance operational effectiveness.

Finally, blockchain adoption also opens up new financing opportunities for SMEs. With the ability to provide transparent, real-time data on their financial health and operations, SMEs can offer lenders greater assurance and reduce risk. This, in turn, enables financial institutions to offer more favorable financing terms, helping SMEs to scale

their operations and grow. This is particularly relevant in developing economies, where access to finance is often a challenge for SMEs. Blockchain's capacity to enhance trust and visibility can unlock these much-needed financial resources.

Blockchain technology offers SMEs an array of strategic opportunities to innovate, grow, and enhance their sustainability credentials. By fostering partnerships with larger firms, entering new markets, leading in niche sustainable practices, and automating supply chain processes, SMEs can not only overcome the challenges associated with blockchain adoption but also position themselves as leaders in the future of sustainable supply chain management. While the initial costs and technical complexity of blockchain implementation may pose challenges, the long-term benefits far outweigh these obstacles. As blockchain technology continues to evolve, its potential to drive innovation and create value for SMEs will become increasingly evident, making it a critical tool for those looking to gain a competitive advantage in the digital economy.

SMEs that recognize and seize the opportunities presented by blockchain will be better equipped to navigate the complexities of modern supply chains, particularly in regions where infrastructure and regulatory environments are evolving. As global markets continue to demand more transparency and sustainability from their supply chains, blockchain will undoubtedly play an essential role in shaping the future of commerce, and SMEs that embrace it will be well-positioned for long-term success.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest is to be disclosed.

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