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(REVIEW ARTICLE)

Comprehensive framework for data fusion in distributed ledger technologies to enhance supply chain sustainability

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Abstract

This review proposes a comprehensive framework that integrates data fusion with Distributed Ledger Technologies (DLT) to enhance sustainability in supply chain management. In today's global supply chains, ensuring transparency, efficiency, and environmental responsibility is critical, yet the lack of real-time visibility and data fragmentation presents significant challenges. The framework addresses these issues by merging data from multiple sources, including IoT devices, operational databases, and external environmental factors, using advanced data fusion algorithms. DLT, with its decentralized, immutable, and transparent nature, ensures the integrity and security of the data, allowing all stakeholders to access accurate and tamper-proof information. The fusion of data within a DLT infrastructure not only improves traceability and accountability but also enables the automation of sustainability checks via smart contracts. These contracts can trigger actions based on predefined sustainability metrics such as carbon emissions, energy consumption, and resource efficiency. Furthermore, predictive analytics and machine learning algorithms integrated into the system provide real-time monitoring and optimization of sustainability performance throughout the supply chain. The proposed review offers numerous benefits, including enhanced transparency, reduced operational costs, improved sustainability outcomes, and risk mitigation. It also addresses challenges such as scalability, data privacy, and regulatory compliance, offering solutions to overcome these hurdles. By exploring case studies of successful implementations, this review demonstrates the practical applications and future potential of combining DLT and data fusion for sustainable supply chain management, positioning it as a critical tool for organizations aiming to meet environmental and regulatory demands in an increasingly digital and eco-conscious world.

Keywords: Data Fusion; Ledger Technologies; Supply Chain; Review

1 Introduction

Distributed Ledger Technologies (DLTs), such as blockchain, have garnered significant attention due to their ability to provide decentralized, transparent, and immutable records of transactions (Ige *et al.*, 2024). In a DLT, a distributed network of participants maintains a shared ledger, which is updated and validated through consensus mechanisms without relying on a central authority (Harrison *et al.*, 2024). This ensures that the data remains secure, tamper-proof, and transparent to all stakeholders. One of the most well-known implementations of DLT is blockchain, which has seen broad applications in areas ranging from cryptocurrency to supply chain management. By removing intermediaries and automating trust through cryptographic protocols, DLTs have the potential to transform complex, multi-stakeholder industries like global supply chains (Samira *et al.*, 2024).

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Sustainability in modern supply chains has emerged as a critical focus area, driven by the increasing demand from consumers, governments, and businesses to reduce environmental impact, promote ethical labor practices, and ensure responsible sourcing (Agu *et al*., 2023). Supply chains often involve multiple tiers of suppliers across various regions, which adds complexity to monitoring and ensuring sustainable practices. As a result, businesses are under pressure to increase transparency, traceability, and accountability in their operations. Sustainable supply chains aim to optimize resource use, reduce waste and emissions, and ensure that social and ethical standards are upheld throughout the production process (Okeke *et al*., 2024).

Despite the growing importance of sustainability, traditional supply chain management methods face several challenges (Komolafe *et al*., 2024). These include fragmented data systems, manual processes, and limited visibility into the operations of suppliers and sub-suppliers. The need to collect and analyze data from diverse sources ranging from environmental impact reports to product lifecycle data has become paramount. This is where data fusion comes into play. Data fusion refers to the process of integrating and analyzing data from multiple sources to provide a unified view, enabling better decision-making (Adeniran *et al*., 2024). In the context of supply chain management, data fusion can enhance operations by allowing businesses to combine data from various stakeholders, track sustainability metrics in real-time, and ensure compliance with environmental regulations.

The purpose of this review is to address the current inefficiencies in supply chain sustainability by integrating DLTs and data fusion methodologies. Today, many supply chains suffer from limited transparency, inefficient data-sharing mechanisms, and difficulties in verifying sustainability claims (Odonkor *et al*., 2024). These challenges are compounded by the globalized nature of supply chains, where a lack of trust between stakeholders and the fragmentation of data systems impede sustainable decision-making. By leveraging DLT, this framework aims to create a decentralized, immutable record of sustainability-related data across the supply chain (Iriogbe *et al*., 2024). This enhances transparency by allowing all stakeholders to access verified, real-time information on the sustainability practices of each actor in the chain. Data fusion complements this by integrating data from various sources such as environmental sensors, supplier reports, and regulatory documents and fusing it into a single, reliable dataset. The combination of DLT and data fusion thus creates a powerful tool for improving sustainability in supply chains (Obiki-Osafiele *et al*., 2024).

The integration of DLT with data fusion not only enhances transparency but also improves accountability and efficiency (Esiri *et al*., 2024). Smart contracts, an integral part of DLTs, can automate and enforce sustainability agreements between parties, ensuring that all stakeholders comply with agreed-upon environmental and social standards. Moreover, this review allows for real-time monitoring of key sustainability metrics, such as carbon emissions, resource use, and waste reduction, providing businesses with actionable insights to optimize their operations. In the long run, this increased accountability and efficiency not only benefits the environment but also enhances the reputation and competitiveness of businesses that adopt sustainable practices. This review addresses the need for a more transparent, accountable, and efficient approach to managing sustainability in supply chains. By integrating the decentralized, secure nature of DLT with the analytical power of data fusion, it provides a comprehensive solution to the challenges of modern supply chain sustainability (Agu *et al*., 2022). Through this framework, businesses can gain real-time visibility into their supply chain operations, ensuring that they meet sustainability goals while maintaining efficiency and competitiveness.

2 Overview of Distributed Ledger Technologies (DLTs)

Distributed Ledger Technologies (DLTs) refer to a class of digital systems that allow data to be stored, shared, and updated across a decentralized network of participants, rather than relying on a central authority or database (Efunniyi *et al*., 2022). The key feature of DLTs is that every participant in the network maintains a copy of the ledger, and updates to the ledger are made through a consensus mechanism that ensures consistency and security across the network. This decentralized structure offers several core principles that make DLTs transformative in many industries, including supply chain management.

In DLTs, no single entity controls the data or the network. Instead, control is distributed among participants, reducing the risk of central points of failure and enabling peer-to-peer transactions without intermediaries (Harrison, 2024). This decentralization ensures that data can be shared securely between parties without needing to rely on trust in any single participant. DLTs provide transparent access to the ledger's history, enabling participants to verify transactions and trace the flow of information or assets. This transparency is especially valuable in industries like supply chain management, where stakeholders need real-time access to accurate data regarding product origin, movement, and compliance with sustainability standards (Adeniran *et al*., 2024). Once data is recorded on the ledger, it becomes immutable meaning it cannot be altered or tampered with. This property ensures that transaction histories are secure and verifiable, making DLTs ideal for creating trust in data integrity. DLTs rely on consensus protocols to validate and agree on transactions. These mechanisms, such as Proof of Work (PoW), Proof of Stake (PoS), or Byzantine Fault

Tolerance (BFT), ensure that participants reach a consensus on the state of the ledger without the need for a central authority. This consensus provides a secure method for confirming the accuracy of transactions in a decentralized environment, making it an essential feature of DLT security.

DLTs are not a monolithic technology but come in various forms, each with unique properties that suit different use cases (Ikevuje *et al.*, 2024). Some of the most prominent types of DLTs include. The most well-known type of DLT, blockchain operates as a chain of blocks, where each block contains a list of transactions. Once a block is validated and added to the chain, it becomes immutable. Blockchain's combination of decentralization, transparency, and security has led to its adoption in various sectors, particularly for applications such as cryptocurrencies (e.g., Bitcoin) and smart contracts. In supply chains, blockchain enables the transparent and secure tracking of goods from source to end consumer. Hashgraph is an alternative to blockchain that offers faster transaction speeds and greater scalability. Instead of chaining blocks, Hashgraph uses a gossip protocol to share information among participants, which is then used to validate transactions through a consensus mechanism known as Byzantine Fault Tolerance (BFT). Its high throughput and efficiency make it attractive for real-time applications in industries like finance and supply chain management, where large volumes of data need to be processed quickly and securely. Unlike blockchain, which relies on a linear sequence of blocks, Directed Acyclic Graph (DAG) operates as a graph structure where each transaction validates one or more previous transactions (Adewumi *et al.*, 2024). This structure allows for faster and more scalable networks, particularly in environments where high transaction throughput is necessary. DAGs are useful in supply chains that need to handle large amounts of transaction data without bottlenecks, enabling smoother and more efficient operation. Other emerging DLTs, such as Corda and Quorum, offer specialized features like permissioned networks, where only approved participants can join and validate transactions. These types of DLTs are often used in enterprise settings, where privacy and compliance with regulations are critical.

DLTs have a wide range of applications in supply chain management (SCM), especially in addressing issues related to transparency, efficiency, and sustainability (Ekpe, 2022). Some of the most impactful applications include. DLTs enable the tracking of goods and products throughout their lifecycle, from raw material sourcing to final delivery. Blockchain, for example, can store immutable records of each step in the supply chain, ensuring that all participants have access to verified data on the product's origin, handling, and transport. This transparency is crucial for ensuring compliance with sustainability standards, verifying ethical sourcing, and reducing fraud in supply chains. Smart contracts are self-executing contracts with the terms of the agreement directly written into code (Agu *et al.*, 2024). These contracts are stored and run on DLT platforms like blockchain and can automatically enforce compliance with agreed-upon terms. In supply chain management, smart contracts streamline processes such as payments, order fulfillment, and quality assurance, reducing delays and ensuring accountability among stakeholders. DLTs provide enhanced risk management capabilities by enabling real-time visibility into supply chain operations (Okeke *et al.*, 2022). With immutable records of every transaction, supply chain managers can identify bottlenecks, delays, or risks related to non-compliance with sustainability standards. Additionally, DLTs reduce the risk of data manipulation or fraud by ensuring that all parties in the supply chain have access to verifiable and tamper-proof data. Distributed Ledger Technologies offer transformative solutions for supply chain management, enhancing transparency, security, and efficiency. By enabling decentralized data storage, real-time tracking, and automated contract enforcement, DLTs have the potential to significantly improve the sustainability and reliability of global supply chains (Abdul-Azeez *et al.*, 2024).

2.1 Data Fusion in Supply Chains

Data fusion refers to the process of integrating and synthesizing data from multiple sources to create a comprehensive and coherent view of information that enhances decision-making (Ekemezie and Digitemie, 2024). In the context of supply chains, data fusion is particularly important as it allows organizations to merge diverse datasets from various stakeholders, technologies, and operational processes. This integration is essential for improving the accuracy and reliability of supply chain information, ultimately leading to more informed decision-making and enhanced operational efficiency.

The significance of data fusion in supply chains extends beyond simple data aggregation. By combining data from multiple sources such as suppliers, logistics providers, and customers organizations can derive actionable insights that drive better business outcomes. This capability is especially critical in today's fast-paced business environment, where delays or inaccuracies in data can result in lost opportunities, increased costs, and diminished customer satisfaction. Furthermore, data fusion plays a crucial role in sustainability metrics (Reis *et al.*, 2024). By integrating data related to resource consumption, waste generation, and environmental impact, organizations can assess their performance against sustainability goals. This holistic view allows companies to identify inefficiencies, optimize resource use, and reduce their carbon footprint, thereby enhancing their overall sustainability efforts.

In the realm of supply chain management, various types of data contribute to effective data fusion. Understanding these different data types is essential for leveraging data fusion techniques effectively (Agu *et al*., 2024). The Internet of Things (IoT) has revolutionized supply chain operations by enabling real-time data collection through interconnected devices and sensors. For example, sensors can track temperature and humidity during the transport of perishable goods, providing critical information that can be fused with other data sources to ensure product quality and safety. This data type encompasses records of transactions between parties in the supply chain, such as purchase orders, invoices, and shipping documents. Transactional data is vital for understanding financial flows, inventory levels, and the overall health of the supply chain. By fusing transactional data with operational and environmental data, organizations can create a more holistic view of their supply chain performance (Harrison *et al*., 2024). Operational data refers to information about the day-to-day operations of the supply chain, including production schedules, lead times, and labor utilization. This data is crucial for assessing efficiency and identifying bottlenecks in the supply chain. When combined with sensor and transactional data, operational data can help organizations optimize their processes and improve responsiveness to market demands. With increasing attention on sustainability, environmental data has become a key component of supply chain analysis. This data includes information about resource consumption, emissions, and waste generation. By integrating environmental data with other types of data, organizations can evaluate their sustainability performance and make informed decisions to reduce their environmental impact (Uzougbo *et al*., 2024).

Despite the clear benefits of data fusion in supply chains, several challenges impede effective data handling and integration. These challenges include. Many organizations operate using multiple disparate systems and applications for managing supply chain data. This fragmentation makes it difficult to aggregate and synthesize data from various sources, leading to inconsistencies and gaps in information (Ogedengbe *et al*., 2024). Data silos occur when departments or stakeholders within an organization fail to share information with one another. In supply chains, this can result in a lack of collaboration and hinder effective data fusion. When different teams maintain separate datasets, it becomes challenging to gain a unified view of supply chain operations, making it difficult to respond swiftly to disruptions or changes in demand (Agu *et al*., 2024). Real-time visibility is essential for effective supply chain management, as it enables organizations to monitor and respond to events as they happen. However, many supply chains still rely on batch processing and periodic reporting, which can result in outdated information. Without real-time visibility, decision-makers may operate based on stale data, leading to missed opportunities and inefficient resource allocation. Ensuring the quality and consistency of data from multiple sources is another significant challenge. Variations in data formats, measurement units, and definitions can complicate data fusion efforts. Organizations must implement robust data governance frameworks and standardization protocols to address these issues, ensuring that the integrated data is accurate and reliable. Data fusion is a critical capability for enhancing decision-making in supply chains. By merging data from various sources, organizations can improve the accuracy and reliability of their information, ultimately driving operational efficiency and sustainability (Okeke *et al*., 2024). However, to realize the full potential of data fusion, organizations must address the challenges associated with fragmented systems, data silos, and real-time visibility. By overcoming these hurdles, businesses can harness the power of data fusion to optimize their supply chain operations and achieve their sustainability goals.

2.2 Integration of Data Fusion and DLT for Supply Chain Sustainability

In the context of distributed ledger technologies (DLTs), data fusion plays a crucial role in improving the sustainability of supply chains. The process begins with the collection of data from various stages of the supply chain, including raw materials sourcing, manufacturing, transportation, and distribution (Ewim *et al*., 2024). This data can come from Internet of Things (IoT) devices, sensors, enterprise resource planning (ERP) systems, and external databases. Once the data is collected, it is aggregated and integrated into a unified system that ensures seamless communication and coherence across stakeholders.

Data fusion in DLT-based supply chains leverages real-time data for more accurate decision-making. Algorithms are applied to synthesize and analyze this data, allowing for the prediction of future sustainability outcomes such as resource utilization, carbon emissions, or waste generation (Akinsulire *et al*., 2024). By optimizing these metrics, companies can reduce inefficiencies and improve their overall environmental impact. Data fusion algorithms can also be designed to optimize sustainability performance by providing actionable insights. The ability to merge and analyze data from different points in the supply chain helps organizations meet their sustainability goals more efficiently.

One of the most significant advantages of integrating DLTs in supply chains is the use of smart contracts self-executing contracts where terms are encoded in a blockchain or other DLT (Nwosu and Ilori, 2024). Smart contracts can automate supply chain processes based on sustainability-related data inputs. For instance, sensors can measure carbon emissions or energy use during production, and once a predefined sustainability threshold is met, a smart contract may automatically trigger actions such as releasing payments or adjusting production schedules. In addition to automation, smart contracts also ensure compliance with sustainability standards. If a supplier fails to meet an agreed-upon sustainability metric such as using renewable energy sources a smart contract can automatically impose penalties or terminate the contract. This fosters accountability and ensures that every entity in the supply chain adheres to sustainability goals. Moreover, smart contracts facilitate real-time verification and validation of sustainability data, streamlining the auditing process (Ofodile *et al*., 2024). By removing the need for manual intervention, smart contracts reduce human error and ensure that supply chain decisions align with sustainability objectives.

One of the key challenges in traditional supply chains is ensuring the authenticity and integrity of data. DLT addresses this by using decentralized ledgers to record transactions and data entries in an immutable format (Babatunde *et al*., 2024). Once data is entered into the DLT, it cannot be altered or tampered with, which significantly reduces the risk of fraud or manipulation. This ensures data authenticity, creating a trustworthy environment for all supply chain stakeholders. For supply chain sustainability, data integrity is crucial for verifying environmental claims, such as reductions in carbon emissions or the use of ethically sourced materials. By recording these claims on a DLT, organizations can offer verifiable proof to consumers, regulators, and business partners, thus fostering greater transparency. This is particularly important in industries where greenwashing false claims about sustainability is a concern. DLTs help eliminate such practices by providing transparent, immutable records of environmental impact. Furthermore, DLT ensures that all participants in the supply chain have access to the same, verified information (Harrison *et al*., 2024b). This shared, distributed view of data enhances collaboration and fosters mutual trust among stakeholders, as each party knows that the data they are viewing is accurate and unalterable.

Integrating data fusion with DLT enables real-time monitoring and predictive analytics in supply chains, further driving sustainability. Artificial intelligence (AI) and machine learning (ML) algorithms can be applied to the fused data, allowing organizations to identify patterns and trends that contribute to sustainability goals (Ahuchogu *et al*., 2024). These predictive models allow organizations to make proactive decisions, such as adjusting operations to reduce energy consumption during peak demand periods or optimizing transport routes to reduce carbon emissions. The continuous feedback loop enabled by real-time monitoring ensures that supply chain activities are constantly improving in terms of sustainability metrics. Moreover, DLT-based data fusion enables early detection of anomalies in supply chain operations. For instance, if a sensor detects unusually high levels of waste during production, the system can automatically alert managers to address the issue before it escalates, thereby reducing environmental harm and operational inefficiencies. The integration of data fusion and DLT in supply chains offers transformative benefits for sustainability (Abdul-Azeez *et al*., 2024). By enabling real-time data collection, improving transparency, automating processes through smart contracts, and applying predictive analytics, organizations can optimize their operations to meet sustainability goals more effectively. As supply chains become increasingly complex, these technologies will play an essential role in ensuring sustainable and resilient global trade networks.

2.3 Key Components of the Comprehensive Framework

The foundation of the comprehensive framework for supply chain sustainability lies in the integration of diverse data sources. These sources provide the raw data required for data fusion and decision-making processes. Key data sources include IoT devices that monitor real-time conditions, such as temperature, humidity, or energy usage in manufacturing and logistics (Ajiva *et al*., 2024). These devices offer a granular view of operational efficiency and environmental impact. Additionally, RFID tags track the movement of goods throughout the supply chain, providing visibility into location, handling, and conditions. This is especially crucial in industries such as food and pharmaceuticals, where the proper handling of products is critical for sustainability and safety. Operational databases offer data on internal processes such as inventory levels, production rates, and resource consumption. This internal data is essential for measuring performance and identifying inefficiencies. External data sources, such as weather reports, regulatory updates, and market conditions, further enrich the dataset, enabling organizations to predict potential disruptions and adapt accordingly (Iwuanyanwu *et al*., 2024).

Once the data is collected, it must be processed and analyzed to generate actionable insights. Data fusion algorithms and models are essential for synthesizing and integrating data from multiple sources. This step involves cleaning and aggregating the data to form a coherent and accurate representation of the supply chain's performance. Machine learning (ML) and artificial intelligence (AI) models are increasingly used in data fusion to predict and optimize sustainability outcomes (Nwaimo *et al*., 2024). Similarly, statistical methods are used to detect anomalies in data, such as unexpected spikes in resource consumption, which may indicate inefficiencies or environmental risks. In terms of sustainability, these algorithms help organizations predict and track their carbon footprint, water usage, and waste generation. By continuously refining these predictions with real-time data, companies can optimize their operations to reduce environmental impact. Predictive analytics powered by AI further enhances decision-making by forecasting future trends and enabling proactive actions (Ajiga *et al*., 2024). duce energy consumption during peak demand periods, thus improving sustainability metrics. The distributed ledger technology (DLT) architecture forms the backbone of the framework, providing a decentralized and immutable platform for data storage and verification. Blockchain, the most well-known form of DLT, is particularly well-suited for supply chain management due to its ability to create transparent, secure, and traceable records. The choice between permissioned and public blockchains is crucial when designing a DLT architecture for supply chain applications. Permissioned blockchains offer greater control and privacy, as only authorized participants can access or modify data. This is often preferred in supply chains where proprietary information, such as product formulations or trade secrets, must be protected. However, public blockchains, which are open and accessible to all, may be used when transparency and consumer trust are paramount, such as in fair trade or ethically sourced products (Ekemezie and Digitemie, 2024). The DLT architecture ensures that all data entries are immutable and time-stamped, making it impossible to alter records retroactively. This is especially important for sustainability claims, as it provides verifiable proof of compliance with environmental standards and reduces the risk of greenwashing (the practice of making false sustainability claims).

Smart contracts are a critical component of the framework, automating key processes based on predefined sustainability metrics. These self-executing contracts can be programmed to trigger actions when specific conditions related to environmental performance are met. For instance, if a manufacturing facility exceeds a certain carbon emissions threshold, a smart contract can automatically halt production or impose penalties until corrective actions are taken. In supply chains, smart contracts can be used to enforce sustainability checks at various stages, from production to distribution (Agu *et al*., 2024). These contracts can also verify that goods meet environmental certifications, such as fair trade or organic standards, before allowing them to enter the next phase of the supply chain. By automating these checks, smart contracts reduce the need for manual interventions and ensure real-time compliance with sustainability goals. This not only improves operational efficiency but also ensures that sustainability objectives are consistently met across the entire supply chain.

The final component of the framework involves leveraging DLT for compliance and regulatory integration. With increasing pressure from governments and consumers to adhere to environmental regulations and sustainability standards, supply chains must be able to demonstrate their compliance with various legal and environmental requirements (Esiri *et al*., 2024). DLT offers a transparent and immutable record-keeping system that simplifies the auditing process. Regulatory bodies can access the blockchain to verify that companies are complying with environmental laws and sustainability certifications. This is especially valuable in industries where regulations are rapidly evolving, such as electronics, textiles, and agriculture. By integrating compliance requirements directly into the blockchain, the framework ensures that supply chains remain aligned with global sustainability standards (Harrison *et al*., 2024). Smart contracts can automate compliance checks, flagging any discrepancies and ensuring that necessary actions are taken before any legal or regulatory issues arise. The comprehensive framework for sustainable supply chain management leverages DLT, data fusion algorithms, and smart contracts to create a transparent, efficient, and accountable system. By ensuring data integrity, automating sustainability checks, and facilitating compliance, the framework enables supply chains to operate more sustainably while meeting the growing demand for accountability in global trade.

2.4 Benefits of the Framework

The implementation of structured frameworks in various industries, especially within supply chain management, offers numerous benefits that streamline operations, enhance accountability, and lead to more sustainable practices (Eziamaka *et al*., 2024). Among the critical advantages of utilizing such frameworks are enhanced transparency and traceability, improved efficiency and cost savings, better sustainability outcomes, and effective risk mitigation.

One of the significant benefits of structured frameworks is the enhanced transparency and traceability they offer. These frameworks ensure real-time, immutable data across all stages of the supply chain, from raw material sourcing to final product delivery. By providing all stakeholders with access to accurate and up-to-date information, frameworks create a more accountable and open system (Okeke *et al*., 2024). This level of transparency helps businesses maintain compliance with regulations, verify ethical sourcing, and quickly resolve any issues related to the origin or handling of products. Moreover, traceability allows organizations to track and trace the movement of goods or services, ensuring that they can identify the source of any inefficiencies or malpractices. This is particularly important in sectors like pharmaceuticals, food production, and high-tech manufacturing, where product recalls or contamination issues can have severe consequences. Real-time data management enabled by frameworks also strengthens consumer trust, as end-users are assured that the products they receive meet stringent quality and safety standards.

Another key advantage of frameworks is their ability to optimize processes and reduce redundancies, leading to improved efficiency and significant cost savings. Frameworks streamline operations by standardizing procedures, ensuring consistency, and automating routine tasks. This helps eliminate unnecessary steps, reduce delays, and avoid duplications, allowing businesses to complete tasks faster and with fewer resources (Ikevuje *et al*., 2024). By leveraging frameworks, businesses also minimize the risk of human error, as tasks are better coordinated and aligned with pre-established protocols. As a result, there are fewer disruptions, lower operational costs, and improved productivity. Companies are able to allocate resources more effectively, reallocate manpower to value-adding activities, and ultimately boost their bottom line.

In today's business environment, sustainability has become a key concern, and frameworks can contribute significantly to achieving better sustainability outcomes. One of the ways this is achieved is by reducing waste, carbon emissions, and energy consumption through more efficient operations. Frameworks provide the necessary tools and guidelines for businesses to monitor and reduce their environmental impact. By optimizing resource allocation, frameworks can help reduce the overuse of materials, minimize waste generation, and decrease reliance on non-renewable energy sources (Ige *et al*., 2024). This not only benefits the environment but also aligns with growing consumer demand for sustainable products, enhancing the company's reputation and competitive edge in the market. Furthermore, frameworks facilitate the implementation of circular economy practices by enabling better product lifecycle management and waste reduction strategies. Companies can track the use of materials, identify opportunities for recycling, and reduce the environmental impact of their products, contributing to long-term sustainability goals.

Lastly, structured frameworks provide substantial risk mitigation benefits by enhancing security and fraud prevention across the supply chain. The real-time and immutable data enabled by these frameworks help organizations detect and prevent fraud, theft, or tampering. By creating a secure, transparent record of all transactions and operations, frameworks make it more difficult for malicious actors to manipulate data or engage in fraudulent activities (Babatunde, 2024). Moreover, frameworks are often equipped with built-in security protocols that protect sensitive data from unauthorized access or cyber threats. This is particularly important in industries dealing with high-value goods or sensitive customer information, such as finance, healthcare, and technology. Risk mitigation through these frameworks not only protects companies from financial losses but also strengthens compliance with regulatory standards, reducing the risk of fines or legal disputes.

The implementation of structured frameworks brings a wide range of benefits across various industries. Enhanced transparency and traceability ensure better accountability and consumer trust, while improved efficiency and cost savings lead to streamlined operations. Additionally, frameworks play a crucial role in promoting sustainability by reducing waste and energy consumption, and their ability to mitigate risks helps protect businesses from fraud and security breaches (Ahuchogu *et al*., 2024). Ultimately, adopting such frameworks enables organizations to operate more effectively, responsibly, and securely in a rapidly evolving marketplace.

2.5 Challenges and Considerations in Adopting Distributed Ledger Technologies (DLTs)

While Distributed Ledger Technologies (DLTs), such as blockchain, promise enhanced transparency, security, and efficiency, several challenges and considerations must be addressed before widespread adoption (Ajiva *et al*., 2024). These challenges include technical limitations, data privacy and security concerns, interoperability issues, and regulatory and compliance barriers. Understanding these challenges is essential for businesses and governments looking to implement DLT-based systems successfully.

The scalability of DLTs, high computational costs, and latency issues represent some of the most significant technical challenges associated with these technologies. Scalability refers to the ability of the system to handle an increasing volume of transactions and data without compromising performance (Obiki-Osafiele *et al*., 2024). Many DLT systems, particularly public blockchains, face difficulty in scaling up because they rely on consensus mechanisms such as proof of work (PoW), which can slow down transaction processing as network activity grows. In addition, DLTs often have high computational costs due to their decentralized nature. For instance, PoW-based blockchains like Bitcoin require immense computational power to validate transactions, which translates into high energy consumption and expensive hardware requirements. These high costs make it challenging for smaller organizations or industries with limited resources to adopt DLTs at scale. Furthermore, latency issues, which refer to delays in transaction processing and confirmation, can affect the real-time functionality of DLT systems. These delays make it difficult for industries that require high-speed transactions, such as financial services, to rely on DLTs without making compromises in performance.

Balancing transparency with data privacy and protection is another critical challenge when implementing DLTs. One of the main attractions of DLTs is their ability to create transparent, immutable records of transactions that can be accessed by all participants in a network. However, this transparency can conflict with the need to protect sensitive data, particularly in industries where confidentiality is paramount, such as healthcare and finance. Ensuring data privacy while maintaining the benefits of transparency requires complex cryptographic solutions, such as zero-knowledge proofs or advanced encryption techniques (Iyelolu *et al*., 2024). These solutions, while technically feasible, add layers of complexity and can increase costs, posing another barrier to widespread adoption. Furthermore, ensuring data security in decentralized environments is a challenge. While DLTs are considered more secure than centralized systems due to their distributed nature, they are still vulnerable to cyberattacks, such as 51% attacks, where malicious actors can take control of the network by gaining majority computing power. These risks need to be carefully managed to avoid breaches of sensitive data.

Ensuring compatibility between legacy systems and DLT infrastructure presents another substantial challenge. Many organizations, especially large corporations and government agencies, have invested heavily in legacy systems that are not designed to work with DLT technologies. This can create friction when attempting to integrate DLTs into existing infrastructure. Implementing a DLT-based solution would require considerable effort to ensure that the new system is compatible with the old one. Furthermore, different DLT platforms may have distinct protocols and consensus mechanisms, creating interoperability challenges between different DLT systems themselves (Uzougbo *et al*., 2023). Achieving seamless integration requires the development of standardized protocols and cross-platform solutions that can facilitate communication between legacy and DLT systems without sacrificing efficiency or data integrity.

Adapting to international standards and environmental regulations is another major challenge in the widespread adoption of DLTs. The regulatory landscape for DLTs is still evolving, with different countries and regions adopting varying approaches to regulating blockchain-based technologies (Nwaimo *et al*., 2024). This regulatory uncertainty creates difficulties for organizations that operate across borders, as they must navigate different sets of rules regarding data privacy, financial reporting, and the use of decentralized systems. In other industries, businesses must comply with environmental regulations, particularly concerning the high energy consumption associated with some DLT systems, especially those based on PoW mechanisms. Meeting environmental standards requires a shift toward more energy-efficient consensus mechanisms, such as proof of stake (PoS) or other alternatives, but these transitions come with their own set of technical and operational challenges. Moreover, DLTs face challenges in conforming to existing legal frameworks that were designed with centralized systems in mind. Issues such as jurisdiction over decentralized networks, the legal status of smart contracts, and liability in the event of system failure or fraud are still being debated by lawmakers and regulators (Okatta *et al*., 2024). Until a cohesive regulatory framework is established, organizations must tread cautiously to ensure compliance with evolving legal standards.

While DLTs offer transformative potential across industries, the challenges associated with scalability, data privacy, interoperability, and regulatory compliance must be carefully addressed. Overcoming these obstacles will require collaborative efforts from industry stakeholders, regulators, and technology developers to create scalable, secure, and compliant solutions. By addressing these challenges head-on, businesses can unlock the full benefits of DLTs while mitigating risks and ensuring long-term viability in a rapidly changing technological landscape (Esiri *et al*., 2024).

2.6 Case Studies and Applications of DLT and Data Fusion in Sustainable Supply Chains

Distributed Ledger Technologies (DLTs) and data fusion are increasingly being leveraged to enhance sustainability in supply chains. By offering real-time transparency, security, and the ability to integrate data from diverse sources, these technologies are transforming industries such as food, retail, automotive, and energy (Daramola *et al*., 2024). This explores notable examples of DLT and data fusion applications in sustainable supply chains and highlights real-world case studies where their implementation has led to significant improvements.

In various industries, DLTs and data fusion are used to streamline operations, ensure traceability, and minimize environmental impacts. In the food industry, DLTs have been instrumental in tracking the journey of food products from farm to table (Eziamaka *et al*., 2024). Blockchain, a type of DLT, provides an immutable record of each stage of the food supply chain, allowing for quick identification of sources in the event of contamination or fraud. For instance, retailers and consumers can verify that food items are sustainably sourced, organically grown, or ethically produced. The retail sector also benefits from the integration of DLTs and data fusion to improve inventory management, reduce waste, and enhance transparency. By combining data from various touchpoints suppliers, warehouses, and stores retailers can optimize stock levels and reduce unnecessary production or overstocking, minimizing waste and resource consumption (Ige *et al*., 2024). In the automotive industry, DLTs are used to track the sourcing of raw materials such as lithium for electric vehicle batteries. This ensures responsible sourcing and aligns with increasing environmental regulations and consumer demand for sustainability. The energy sector is another area where DLTs and data fusion are proving vital. By integrating renewable energy sources into the grid and enabling peer-to-peer energy trading, blockchain technology ensures that energy consumption and distribution are more transparent, efficient, and sustainable. Smart contracts self-executing contracts with the terms of the agreement written into code facilitate the automation of energy exchanges between producers and consumers, encouraging the use of clean energy (Nwosu and Ilori, 2024).

Several real-world examples demonstrate the effectiveness of DLT and data fusion in enhancing sustainability. Walmart's food traceability initiative is a leading example. By using IBM's blockchain platform, Walmart can track produce from its origin to store shelves, ensuring transparency and safety. This system has significantly reduced the time required to trace the origin of contaminated food from days to seconds, reducing food waste and enhancing consumer trust (Akinsulire *et al*., 2024). Another successful implementation is Maersk and IBM's TradeLens platform, which uses blockchain to streamline global shipping processes. This platform integrates data from over 90 organizations involved in the shipping supply chain, from port authorities to customs agencies, improving the efficiency of shipping operations and reducing review-based processes. By providing real-time, trusted data, TradeLens has reduced inefficiencies, enhanced security, and lowered the carbon footprint associated with maritime trade. These successful implementations showcase how DLTs and data fusion can be used not only to enhance sustainability but also to optimize business processes, reduce costs, and improve the overall transparency of supply chains.

2.7 Future Directions and Innovations in Sustainable Supply Chains: AI, IoT, and DLT Integration

The future of sustainable supply chains will be shaped by the convergence of cutting-edge technologies, including artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), edge computing, and distributed ledger technologies (DLTs). These innovations promise to enhance transparency, efficiency, and sustainability outcomes. One of the most promising areas for innovation in sustainable supply chains is the integration of AI and ML (Ezeh *et al*., 2024). These technologies can analyze vast amounts of data generated throughout the supply chain, enabling predictive analytics that can optimize operations and enhance sustainability. AI-driven predictions for sustainability outcomes allow companies to anticipate demand, identify inefficiencies, and make proactive adjustments to reduce waste, carbon emissions, and resource consumption. This helps to minimize overproduction and waste, contributing to more sustainable practices. Similarly, machine learning algorithms can analyze historical data and environmental conditions to optimize energy consumption in manufacturing and logistics operations, leading to reduced carbon footprints (Babatunde *et al*., 2024). Furthermore, AI can be instrumental in managing supply chain risks related to sustainability. Predictive models can assess potential disruptions, such as extreme weather events or geopolitical instability, and suggest alternative sourcing strategies or transportation routes. These capabilities enable companies to build more resilient and sustainable supply chains. In the future, AI and ML will likely become even more integrated into supply chain management, providing more sophisticated and real-time insights that support sustainability objectives.

The integration of IoT and edge computing into supply chain operations will further revolutionize data collection and real-time decision-making. IoT devices such as sensors, RFID tags, and smart meters can provide continuous data streams from various points in the supply chain, including manufacturing plants, warehouses, and transportation vehicles. This data can be used to track the status of goods, monitor environmental conditions, and optimize logistics in real-time (Ekemezie and Digitemie, 2024). However, one challenge with traditional IoT setups is the latency and bandwidth required to process the massive amounts of data generated by these devices. Edge computing addresses this issue by processing data closer to the source, reducing the need for constant communication with centralized servers. This allows for faster decision-making and more accurate real-time data fusion. In a sustainable supply chain context, IoT and edge computing can significantly improve resource management. For example, real-time monitoring of energy usage in factories can help optimize energy consumption, while sensors on vehicles can track fuel efficiency and recommend the most eco-friendly routes. In the logistics sector, IoT devices can provide data on cargo conditions, such as temperature and humidity, ensuring that perishable goods are transported under optimal conditions, thus reducing spoilage and waste (Okeke *et al*., 2023). Looking ahead, the integration of IoT and edge computing will provide companies with more granular insights into their operations, enabling more efficient and sustainable supply chain management.

DLTs, particularly blockchain, have already demonstrated their potential to increase transparency and traceability in supply chains. In the future, further adoption of DLT in cross-border trade and logistics will be key to driving more sustainable global supply chains. Cross-border trade often involves complex processes and multiple stakeholders, which can lead to inefficiencies, delays, and increased environmental impacts. Blockchain can streamline these processes by providing a secure, immutable ledger of all transactions and events. For example, by recording the origin of raw materials and tracking their journey across international borders, DLTs can ensure compliance with environmental regulations and ethical sourcing standards. This is particularly important for industries such as fashion, electronics, and automotive, where the demand for transparency and sustainability is increasing. A notable example of blockchain's potential in cross-border trade is the TradeLens platform, developed by Maersk and IBM. This blockchain-based platform facilitates the secure sharing of shipping data among all participants in the supply chain, from manufacturers to customs officials (Esiri *et al*., 2024). TradeLens has already demonstrated its ability to reduce reviewwork, streamline logistics, and lower the carbon footprint of shipping operations. In the future, DLT use cases will continue to expand beyond logistics and into other areas such as supply chain financing, where blockchain can enable more efficient and secure financial transactions (Ajiva *et al*., 2024). For example, smart contracts can automate payments based on predefined milestones, reducing the need for intermediaries and accelerating the flow of goods while ensuring sustainable practices are followed throughout the supply chain.

The future of sustainable supply chains will be shaped by the integration of AI, IoT, edge computing, and DLT technologies. AI and ML will provide predictive insights that enable companies to optimize their operations for sustainability, while IoT and edge computing will enhance real-time data collection and decision-making (Uzougbo *et al*., 2024). Additionally, DLTs will play an increasingly important role in ensuring transparency, traceability, and efficiency in cross-border trade and logistics. By leveraging these innovations, businesses can build more resilient, efficient, and sustainable supply chains, contributing to global sustainability goals while maintaining competitive advantage in an evolving marketplace

3 Conclusion

The integration of Distributed Ledger Technology (DLT) and data fusion into supply chains is revolutionizing sustainability efforts. The framework's impact on supply chain sustainability is profound, offering enhanced transparency, traceability, and real-time decision-making capabilities. By leveraging DLT's immutable record-keeping, businesses can track materials, ensure ethical sourcing, and optimize their logistics processes. Data fusion integrates information from multiple sources, helping to reduce waste, minimize carbon emissions, and improve resource efficiency across industries like food, energy, and retail. These technologies are critical to fostering more resilient, efficient, and environmentally responsible supply chains.

The role of stakeholders in implementing the framework is pivotal. Governments, corporations, suppliers, and consumers all play key roles in adopting and promoting these innovations. Businesses must invest in these technologies and collaborate with stakeholders to build transparent, sustainable networks. Regulators are responsible for creating standards that guide the ethical use of DLT and data, while consumers can demand more sustainable practices, pushing companies to act responsibly. Suppliers, too, must align their operations with these frameworks to create an end-to-end sustainable system.

Looking ahead, the future of sustainable supply chains with DLT and data fusion integration*appears promising. With advancements in artificial intelligence, IoT, and edge computing, supply chains will become increasingly automated and data-driven. This will enable more precise predictions, real-time monitoring, and more adaptive, responsive systems. As these technologies mature, global supply chains will continue to evolve, driving sustainability goals, reducing inefficiencies, and promoting transparency on a larger scale. The continued adoption of DLT and data fusion is essential for achieving long-term environmental and economic sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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